Integrated Modeling

What is it?
What does it do for NGST?
What do we do well?
What can we do better?

Gary Mosier

NGST Integrated Modeling Lead

NASA/GSFC Code 531

Gary.E.Mosier.1@gsfc.nasa.gov

301-286-9386

What is Integrated Modeling ?

- To many, this term is simply synonymous with multi-disciplinary analysis and simulation
- This is (all too?) often limited to the so-called “forward modeling problem”, where we model a design, model the loads acting upon the system, model the constraints, etc. and “turn the crank”
- Examples:
  - perform design/requirements verification (example: error budget “bottoms-up” analysis, i.e. margin prediction)
  - perform sensitivity analysis and MDO (multidisciplinary design optimization), albeit often in an awkward and ad-hoc manner
  - simulate output of one system/process for input to another (example: synthetic imagery used to develop/test ground-based software for image post-processing)
  - labs & testbeds: hardware emulation, real-time control
- After 6 years “in the business”, my conclusion is that we should apply a broader meaning to the word integrated than this, but let’s save that for later…

Aside: Concepts of Validation and Verification

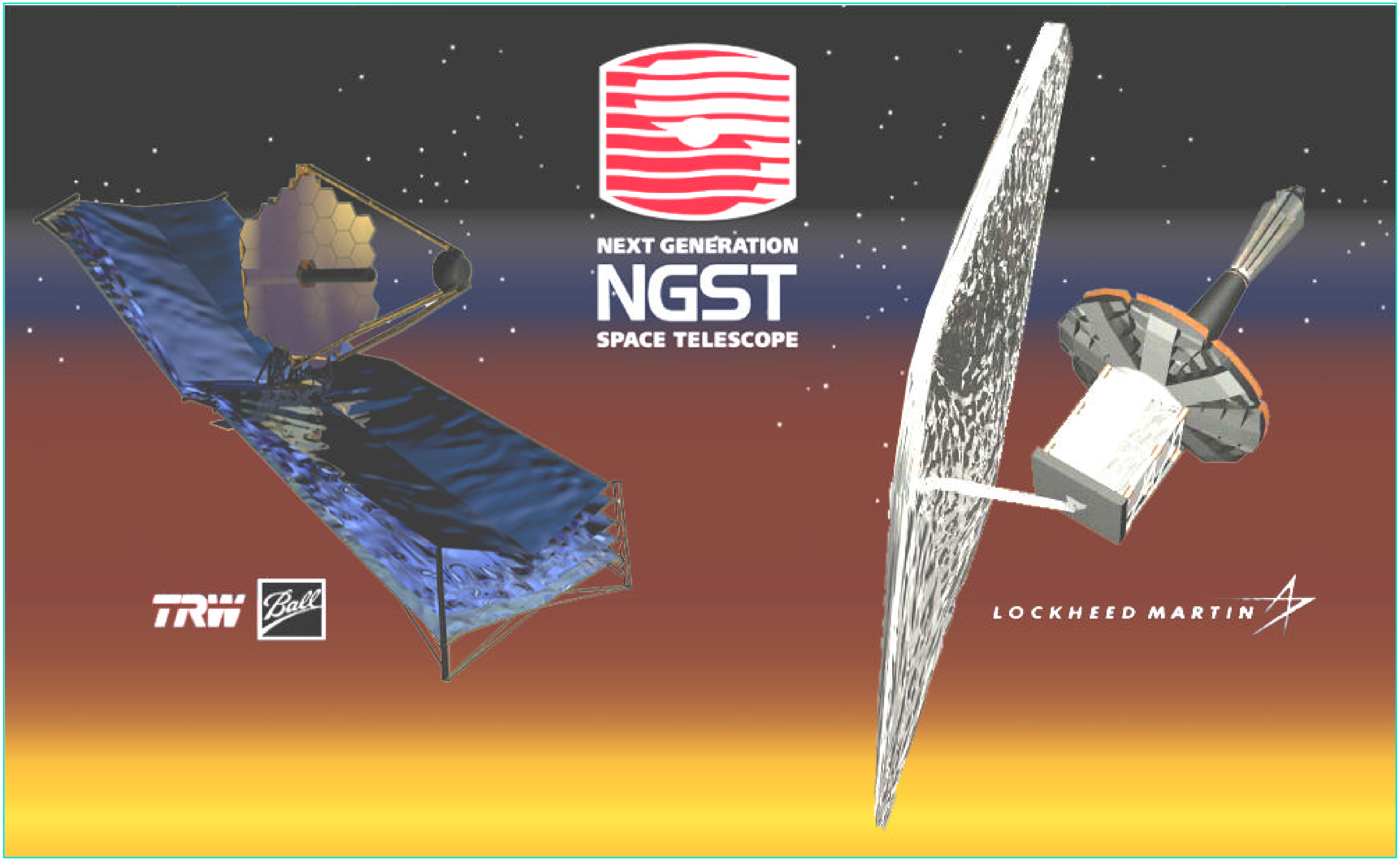
- Ref: John Azzolini, "Essential Systems Engineering: A Lifecycle Process", 1995
- Validation relates to formulation. Answer the question: "Did I build the right model?" A validated model has been shown to properly address the question, issue, requirement, etc. for which it was built. Critical to this process is a thorough vetting of the underlying assumptions, methods, and tools.
- Verification relates to implementation. Answer the question: "Did I build the model right?" A verified model has been shown to accurately parameterized, be "bug-free", etc. Ideally, such a model can accurately predict performances, under a variety of conditions, which are confirmed via hardware test. Sometimes, a model can't be verified until after we launch and deploy.

NGST Modeling Examples: “Yardstick” and “Nexus” studies (circa 1996-2000)

NGST Overview

- Part of the ORIGINS program, the follow-on to Hubble Space Telescope
- Significant work started at GSFC in 1996, currently transitioning between formulation and implementation phases
- Present focus is on major procurements:
  - Prime contractor for optical telescope assembly, sunshield, and systems integration
  - Instruments and detectors
  - Additional contributions from international partners
    - ESA: spacecraft and instrument technology
    - CSA: fine guidance sensor and instrument technology
- Milestones: PDR 2003, CDR 2004, Launch 2009

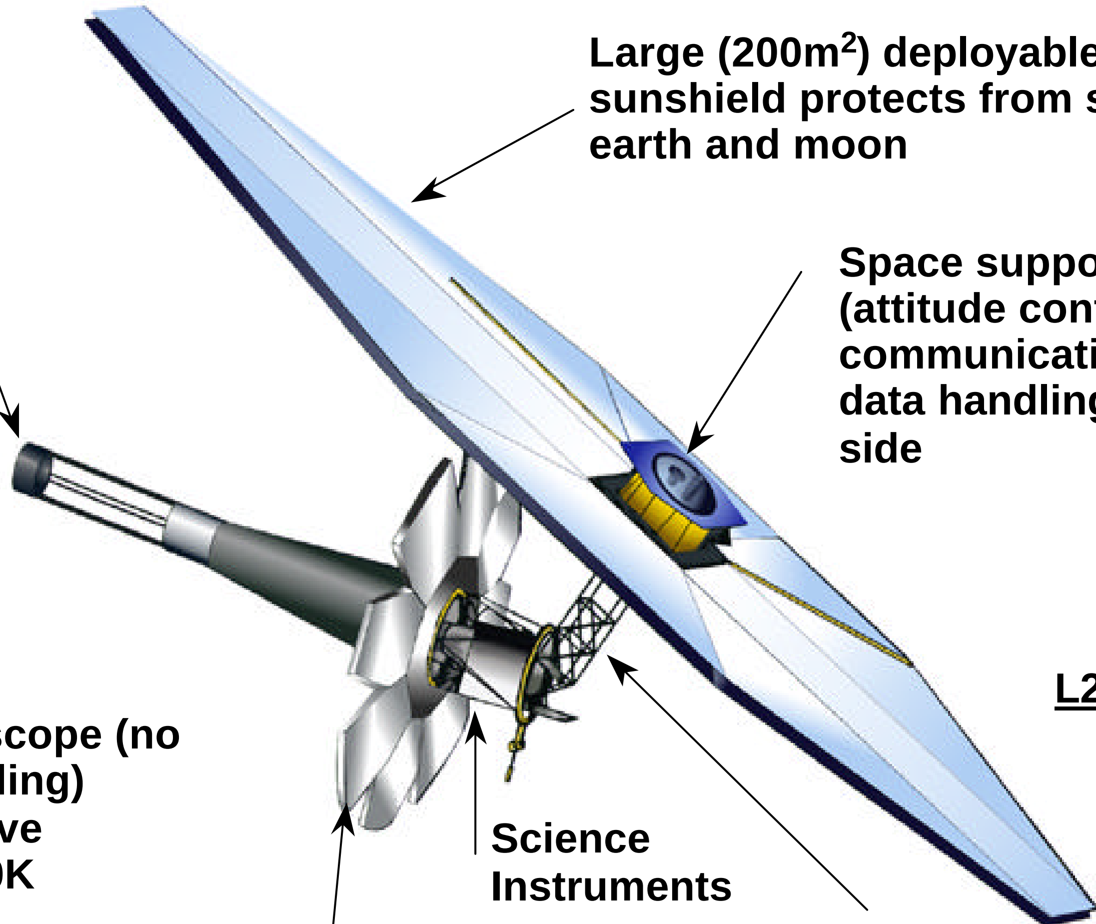
Industry Concepts



Key Science Drivers

- **Mission objectives: study the large scale geometry of the universe, the origin of galaxies, and the nature of the earliest generations of stars**
- **Near-infrared optimized to study red-shifted galaxies**
- **Sensitivity requirement for faint-object detection (specifies point source flux as function of wavelength, filter bandpass, integration time, and signal-to-noise ratio)**
- **Image quality and stability requirements for resolution and operational efficiency**
  - **Diffraction-limited at 2 micron wavelength (Strehl ratio of 0.8)**
  - **Encircled Energy faction GTE 75% within 150 mas radius at 1 micron wavelength**
  - **EE stable within +/- 2% over 24 hour period, and similary stable between major recalibrations**

NGST “Yardstick” Concept



Integrated Modeling throughout the Project Life Cycle

CONCEPTUALIZE

OPTIMIZE/REALIZE

VALIDATE/VERIFY

Mission Life Cycle

GSFC IDC and JPL PDC capabilities

- *very simple analytic models*
- *mission-level parametric analysis*
- *spreadsheet-centric, some CAD tools*
- *oriented toward mission and spacecraft analysis*

NGST/SIM capabilities (IMOS)

- *medium complexity analytic models*
- *subsystem-level parametric analysis*
- *flexible, programmable software environment*
- *linear, non-linear, statistical, simulation*
- *multidisciplinary design optimization with science & cost metrics*

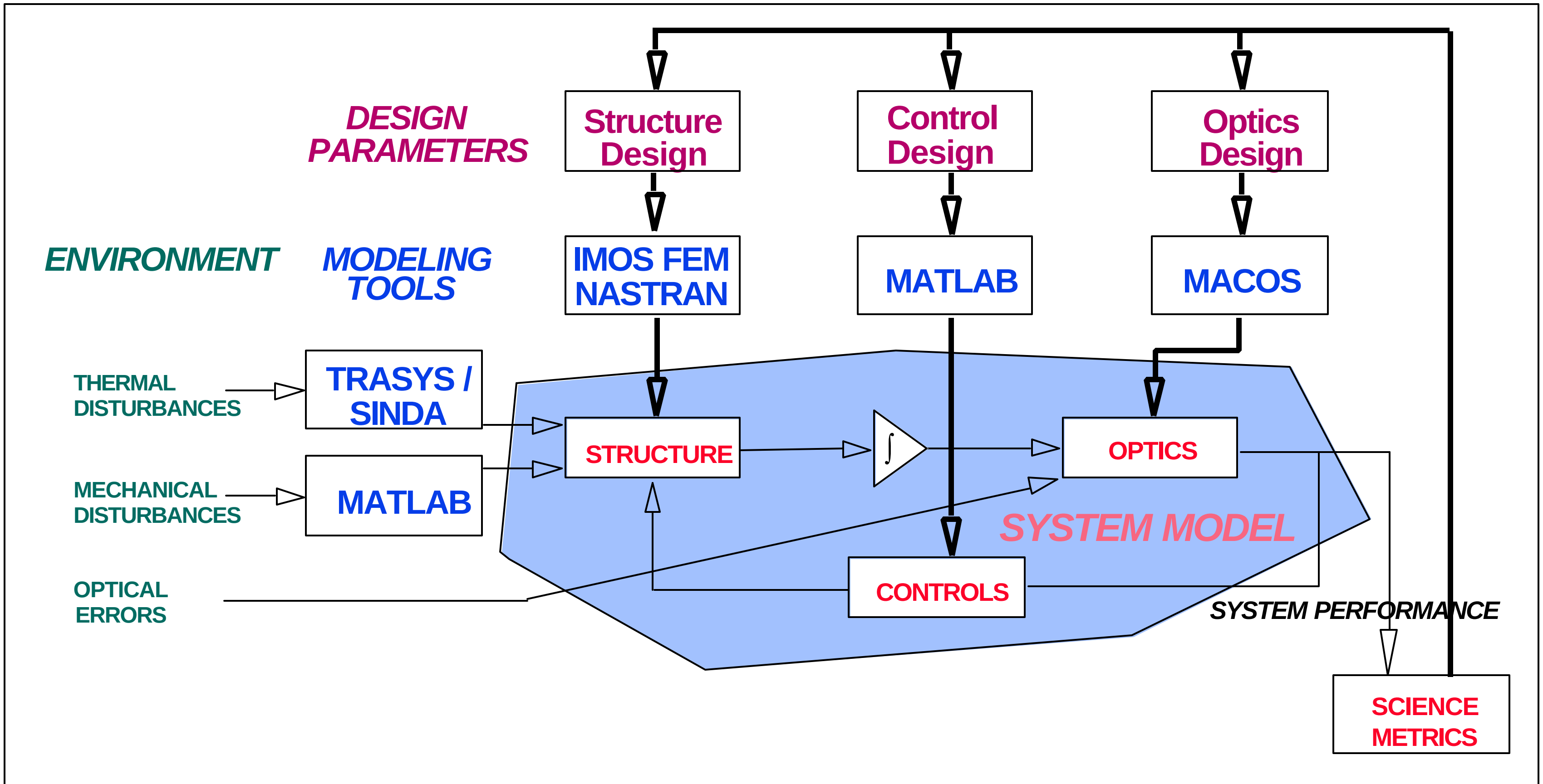
Detailed Design Verification Tools

- *"industry standard" & legacy tools*
- *cumbersome for trades and optimization process*

Virtual Prototype (Flight Simulator)

- *TBD*

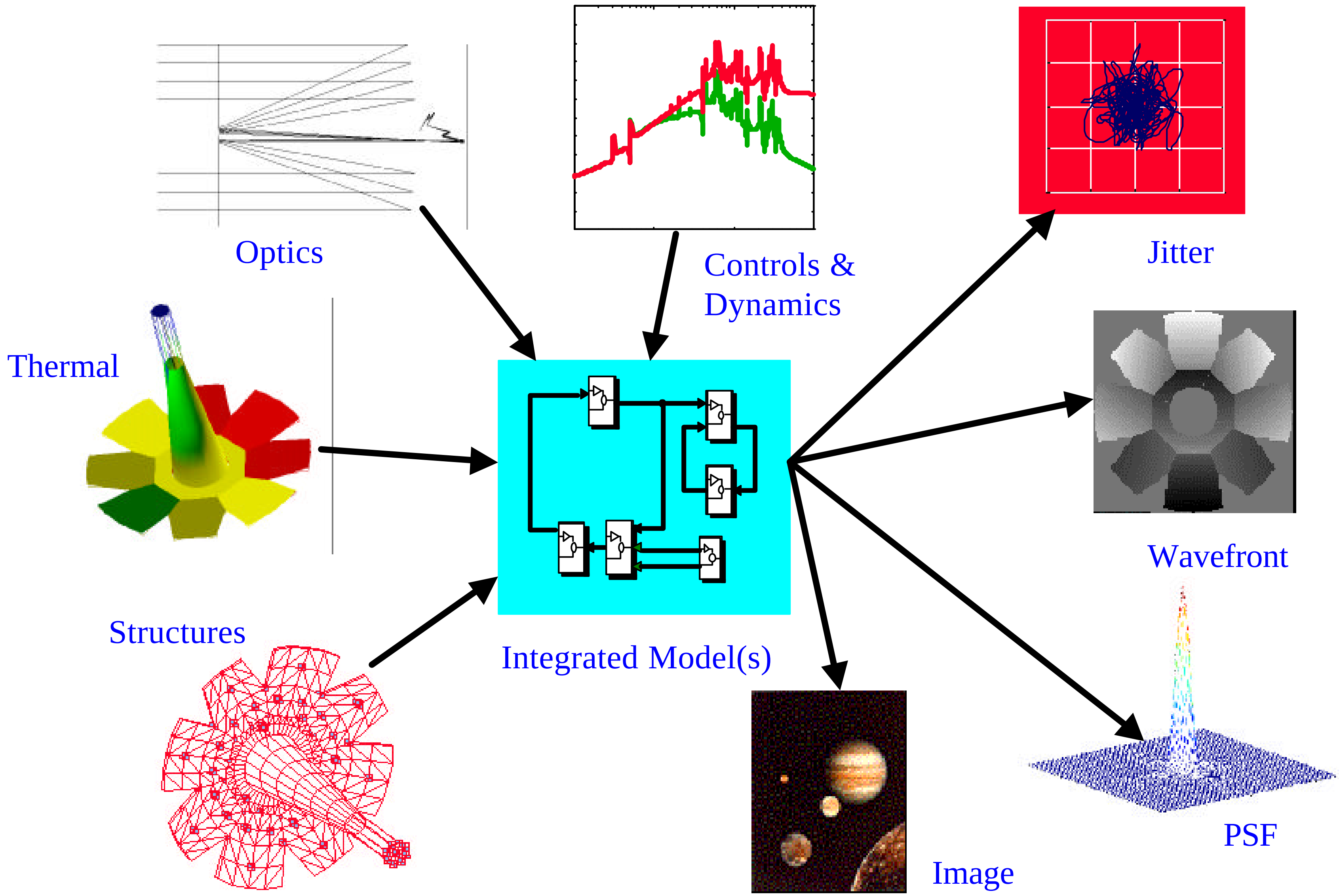
IMOS/MACOS Software Environment



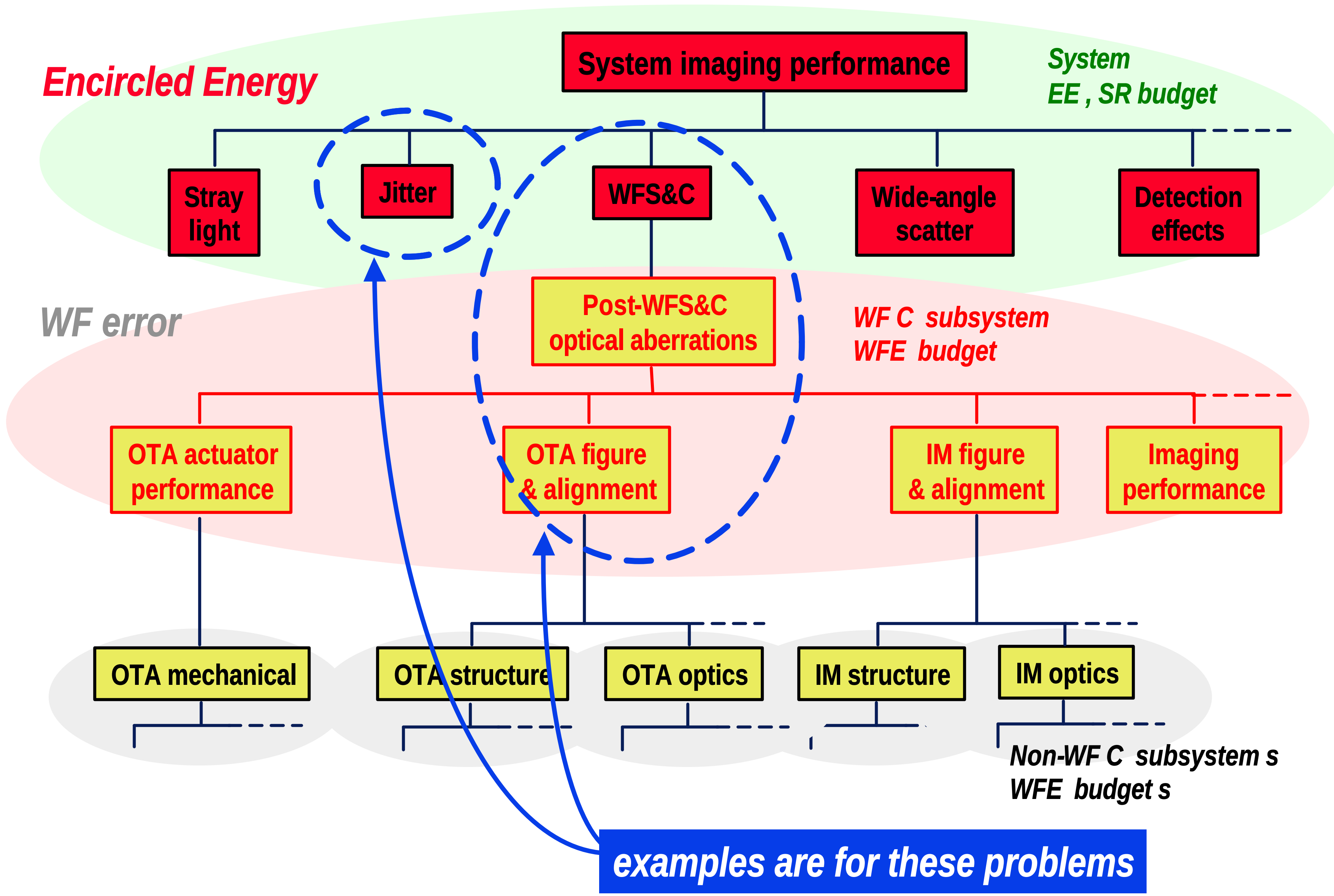
Integrated modeling was applied to investigate many design issues during Phase I studies. Three key problems received the most attention:

- **thermal-elastic deformation of OTA (STOP analysis)**
- **wavefront sensing and control**
- **line-of-sight stability (jitter)**

Key NGST Integrated Analysis Products



NGST System Error Budgets - Example



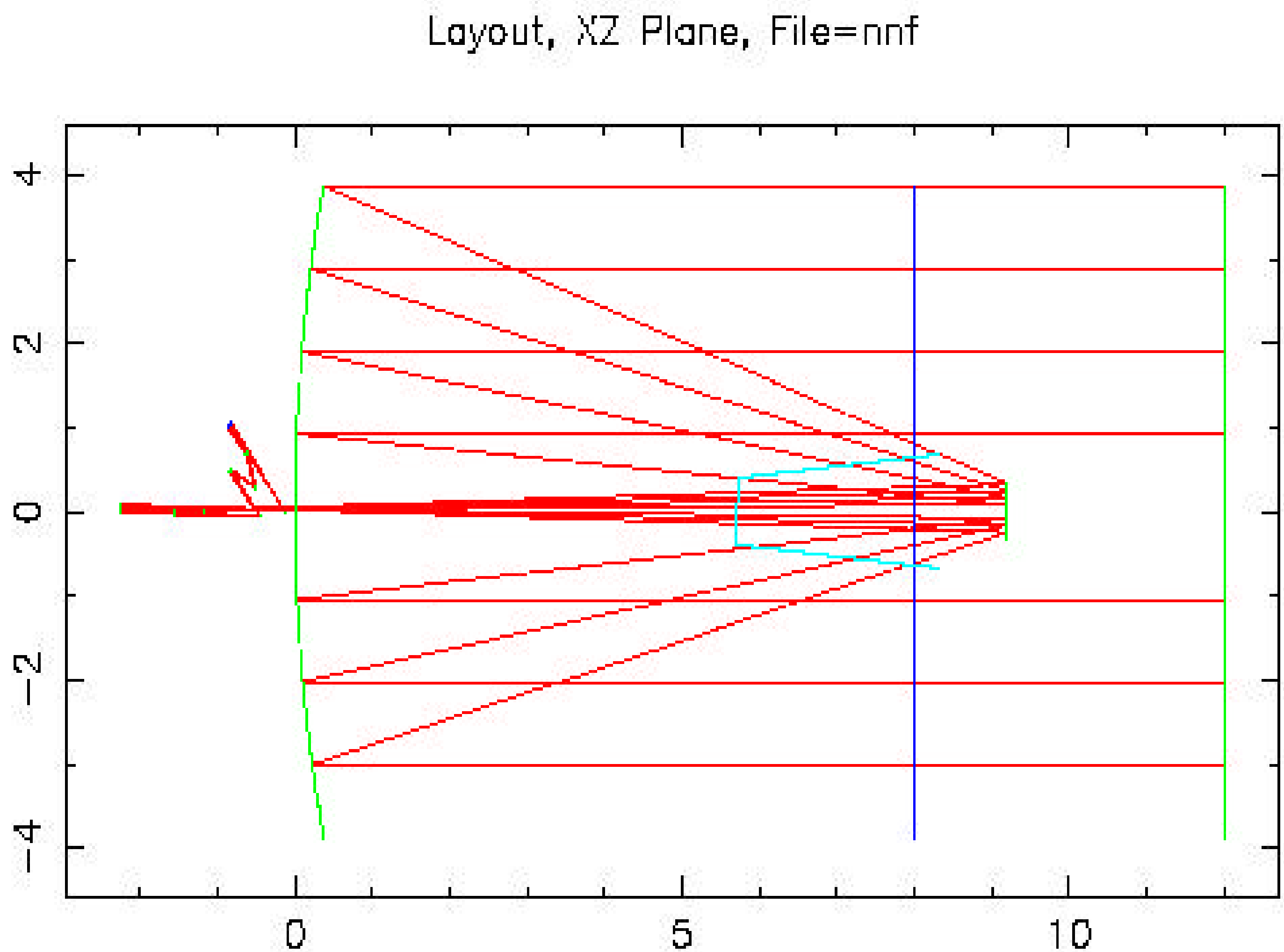
Design Verification Analysis Example #1

"Yardstick" Opto-Mechanical Stability (incl. Wavefront Control)

Example #1 Problem Statement

- Construct a model that simulates the problem of initial alignment and phasing of the optics following launch and deployment.
  - Key assumption: only consider thermal-elastic deformation of the Optical Telescope Assembly
  - Key assumption: wavefront error sensing is perfect
  - Key assumption: wavefront control effected via electro-mechanical actuators (rigid-body on segments plus deformable mirror at pupil)
  - Evaluate the performance of the wavefront control system via STOP analysis coupled to active optics simulation

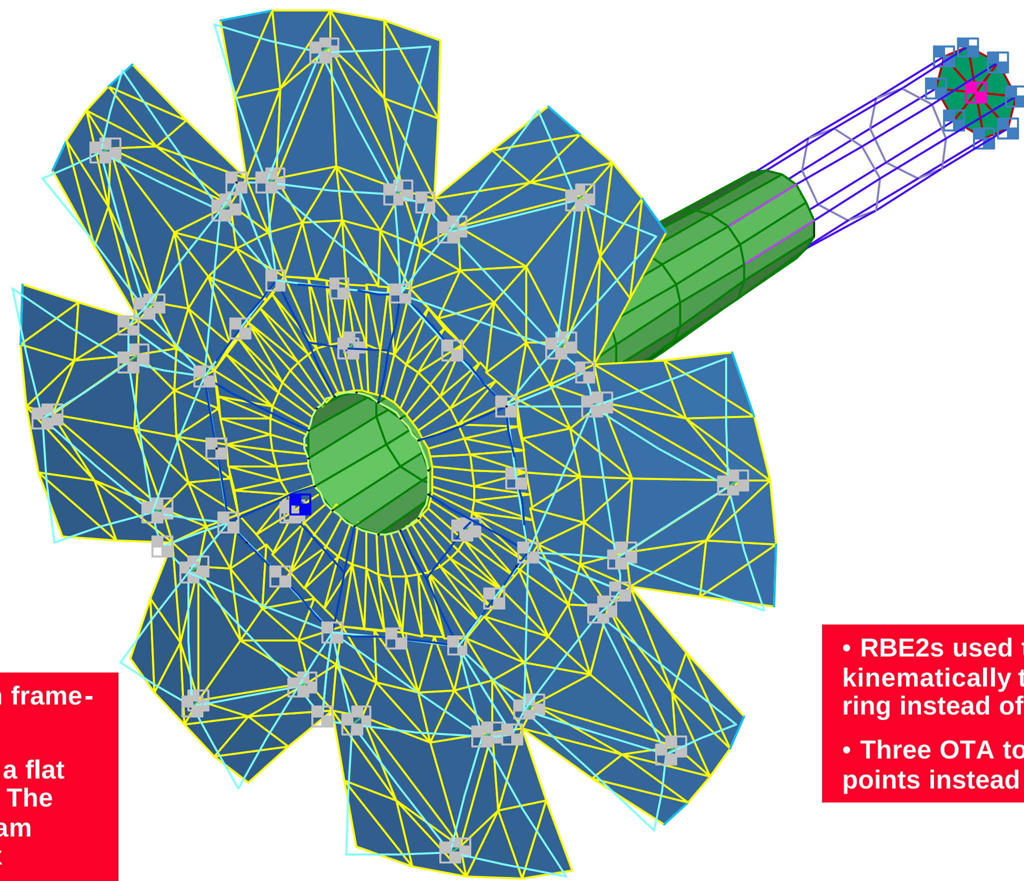
Optical Ray Trace Model (MACOS)



OTA FEM (IMOS)

- recover 1044 DOFs (344 nodes on PM, translation only, plus SM and SI)

- 2.00mm thick face sheet by 4cm deep core orthogrid beryllium mirror shell
- cells are 14.5 cm on a side equilateral triangles,cell wall are 1.00 mm thick

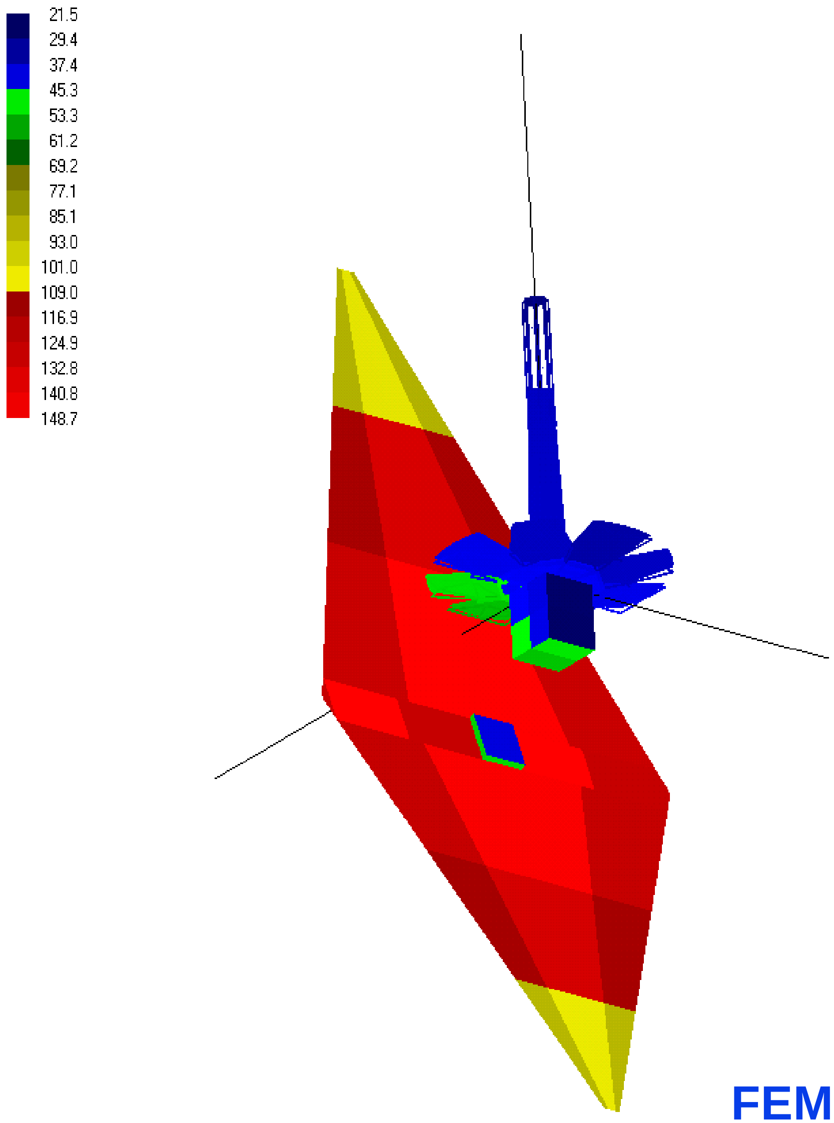


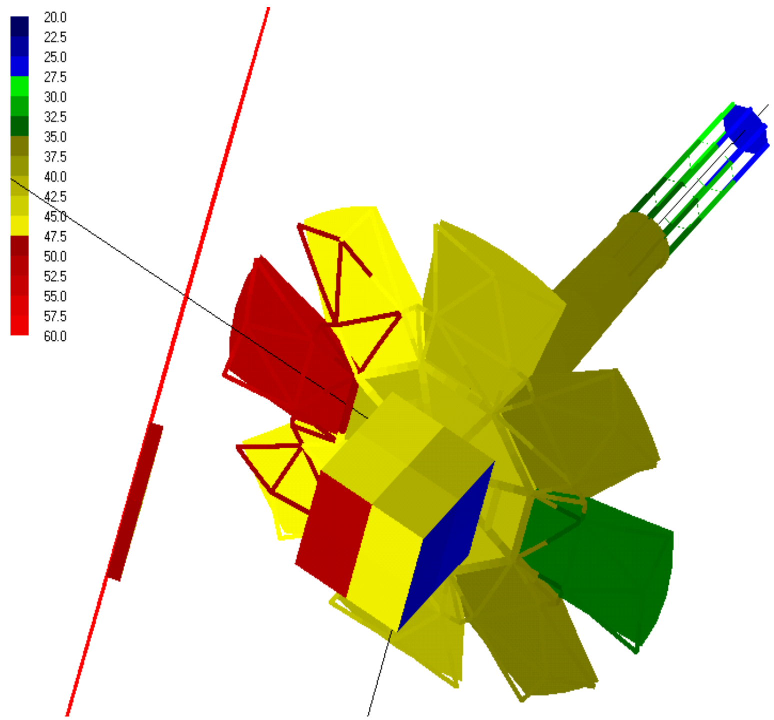
- The petal reaction structure is a beryllium frame-work of I-beams
- The center segment reaction structure is a flat Beryllium frame with a 1.3M dia inner ring. The frame is composed of a 152 mm deep I-beam inner ring and 152mm by 100mm wide box section outer ring and spokes.

- RBE2s used to attach SI kinematically to center main ring instead of CELAS
- Three OTA to S/C I/F points instead of four

PATRAN → NASTRAN → IMOS

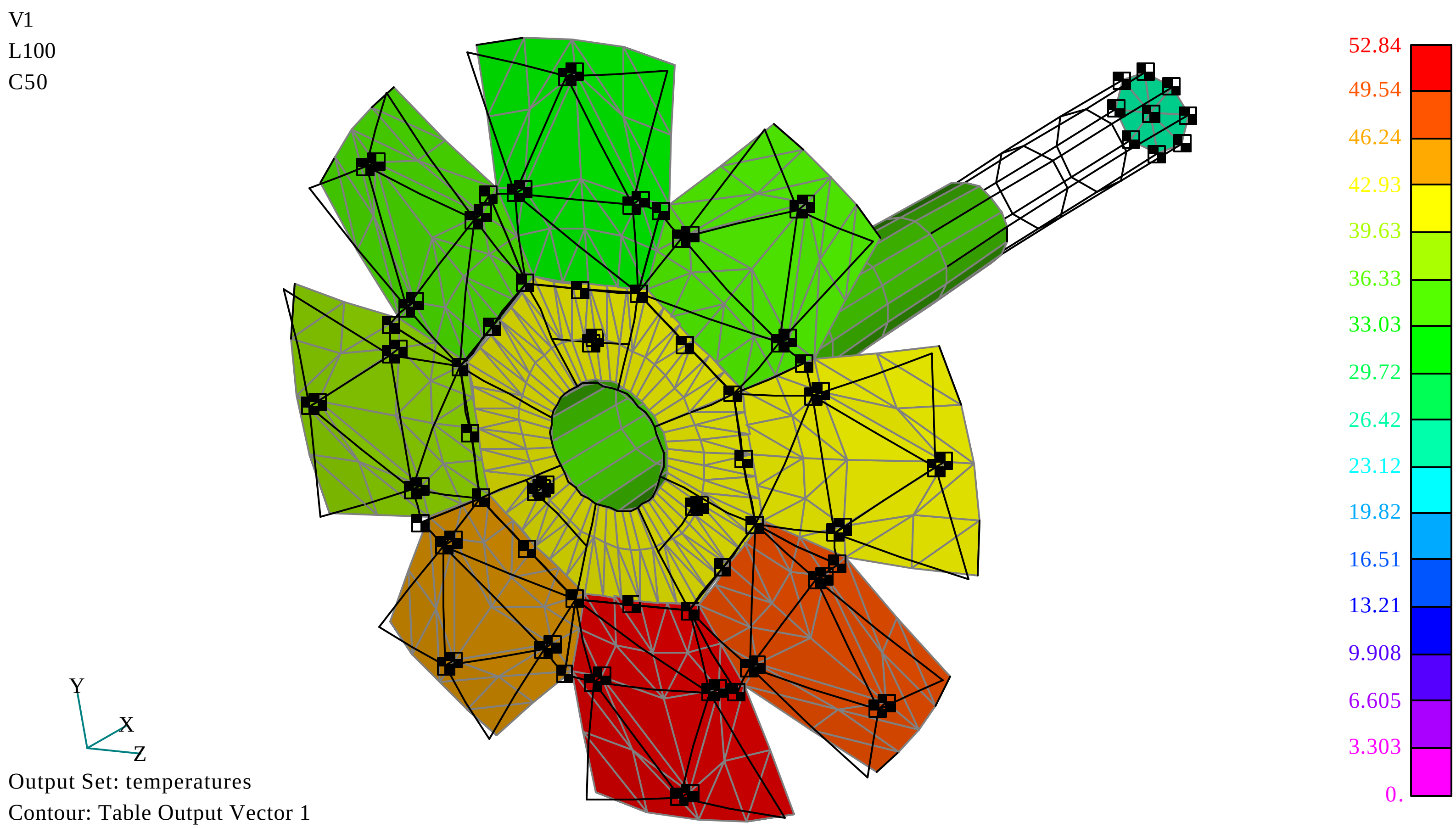
Observatory Thermal Model (IMOS)





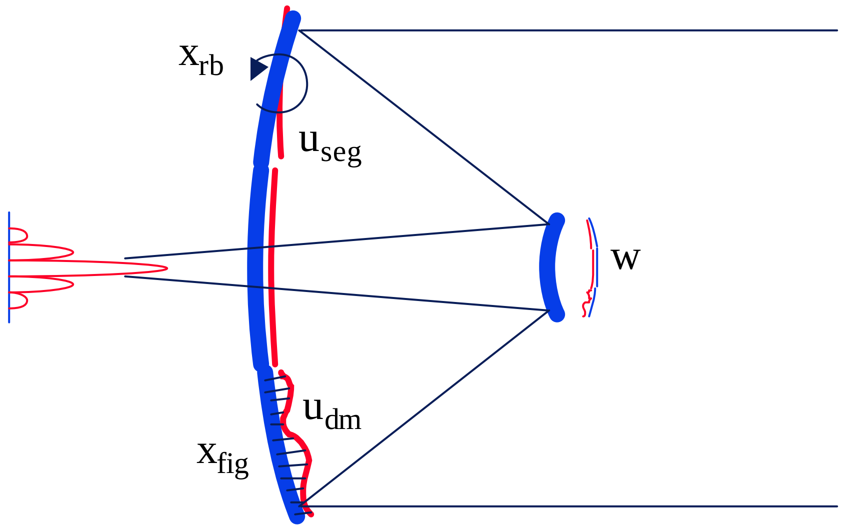
FEMAP → TSS/SINDA → IMOS

Steady State Temps Mapped on OTA FEM



Mapping done by brute-force replication of FEM nodes in the thermal conduction model – not best choice

Linear Error Model for Wavefront Error Analysis



$$x = \begin{bmatrix} x_{segrot} \\ x_{segtrans} \\ x_{IMrot} \\ x_{IMtrans} \\ x_{fig} \\ \vdots \end{bmatrix}$$

Alignment and figure states

$$w = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix}$$

Wavefront sampled at N discrete points in the exit pupil

Optical controls

$$u = \begin{bmatrix} u_{segrot} \\ u_{segtrans} \\ u_{SM} \\ u_{dm} \\ \vdots \end{bmatrix}$$

Linear optical model

$$\mathbf{w_0 = C_x\, x + C_u\, u_0}$$

WF sensing

$$\mathbf{w_{est} = w_0 + dw_{est}}$$

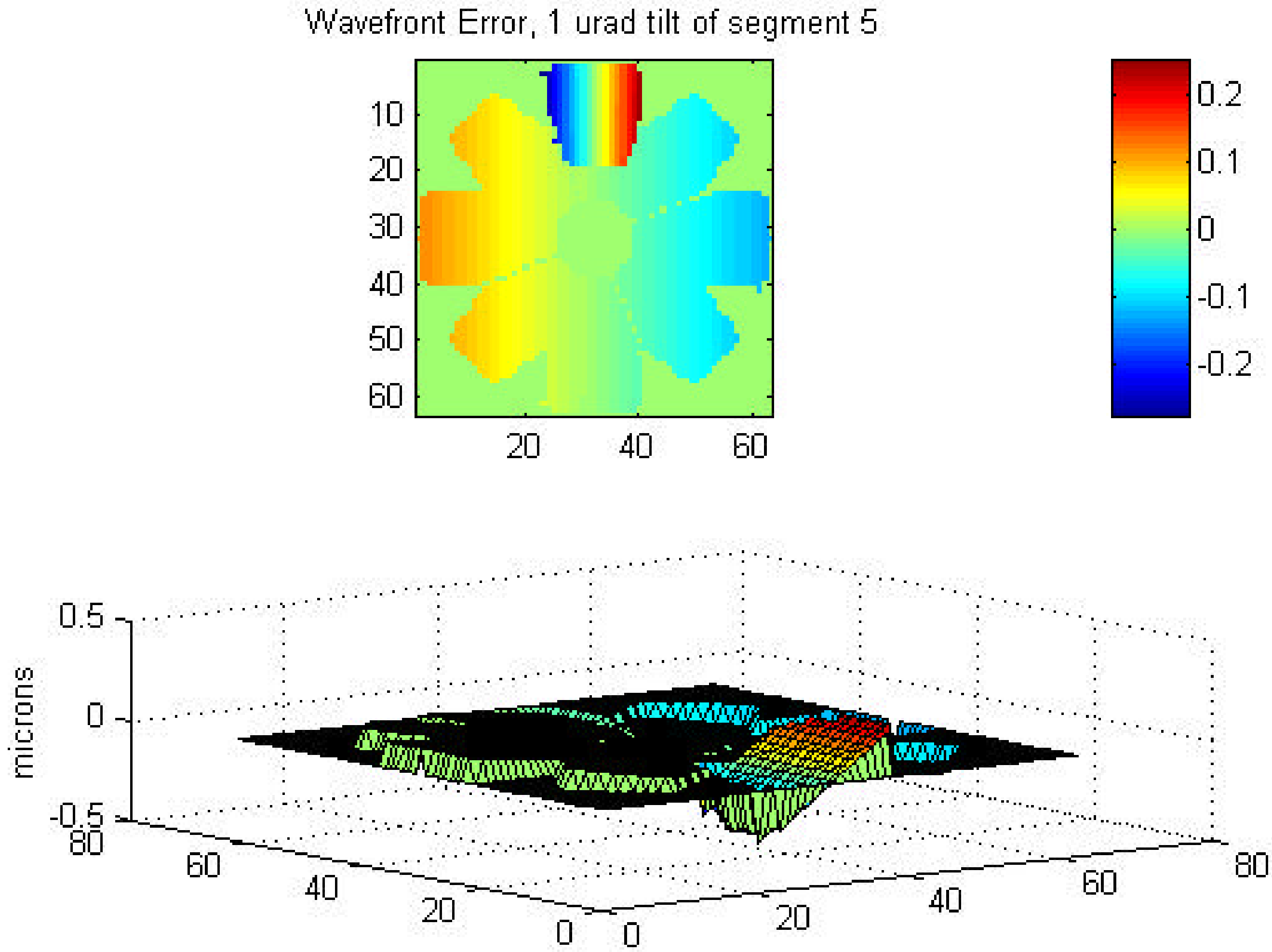
Control

$$\mathbf{u_1 = -G\, w_{est} + du}$$

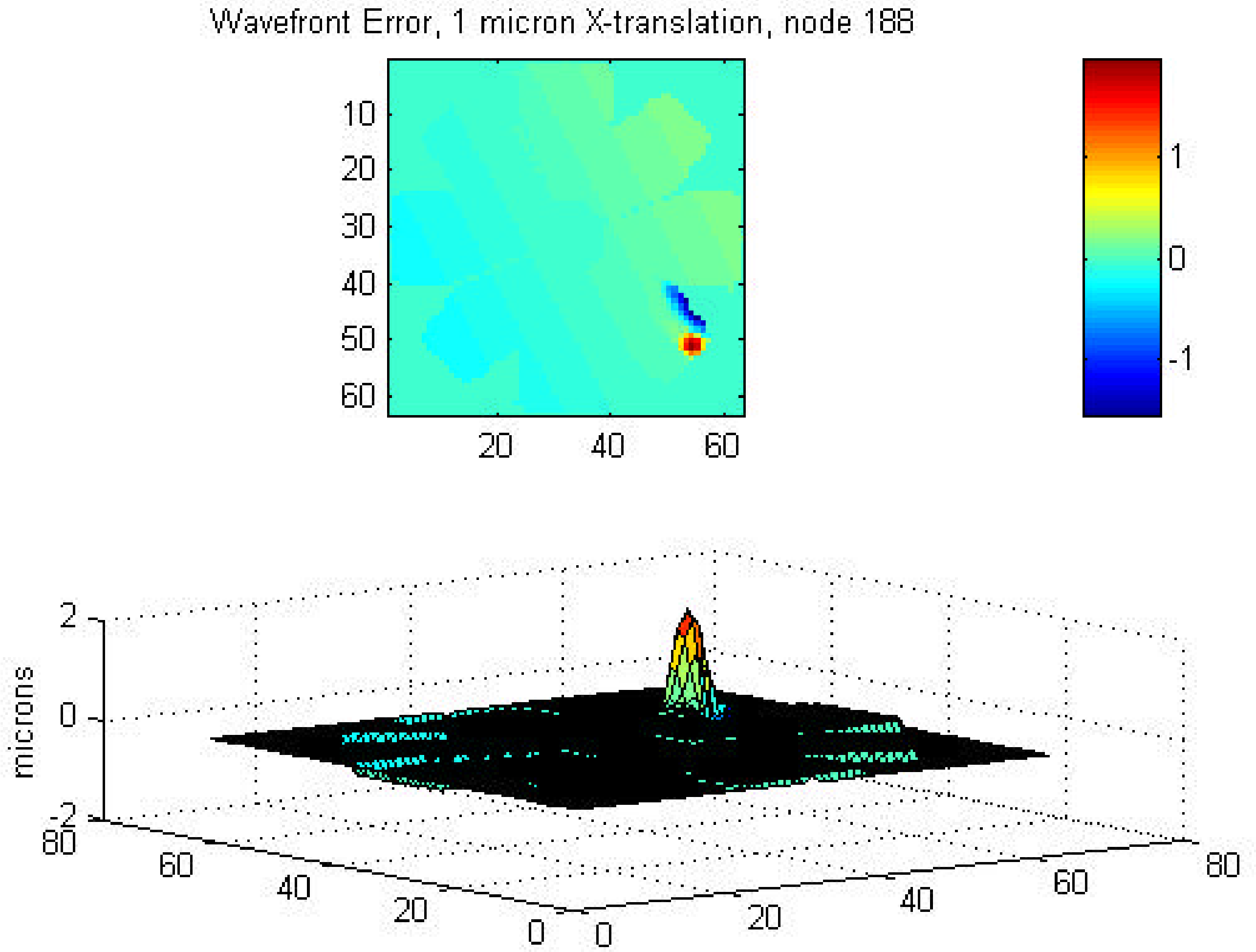
$$\mathbf{G = C_u^{+} = [C_u^T C_u]^{-1}\, C_u}$$

C's are matrices of sensitivity coefficients obtained from perturbation analysis of ray trace model (very difficult to do without MACOS)

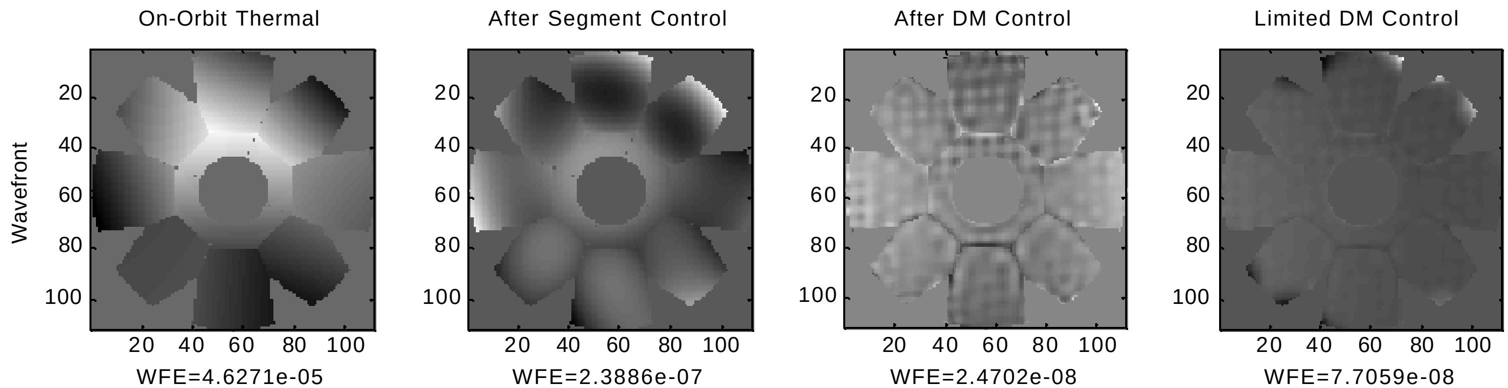
Example: Wavefront Error due to Segment Tilt



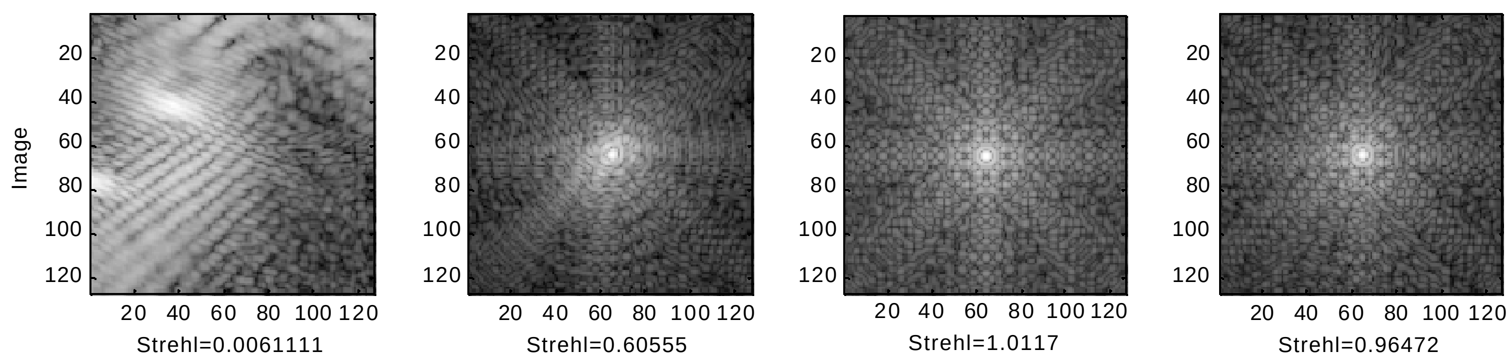
Example: Wavefront Error due to FEM Node Translation



Wavefront Control applied following Ground-to-Orbit Cooldown



Temperatures mapped onto structure → deformations mapped into optics → <u>mechanical</u> control corrects optics



Comments for Example #1

- **Several integrated environments or utilities based on standards (NASTRAN, SINDA, CODE V, etc.) exist or are coming on line:**
  - **IDEAS/TMG**
  - **FEMAP/TCON**
  - **Thermal Desktop**
  - **OptiOpt**
  - **IODA**
- **The above are typical of “glueware”, where data passed between applications “in the pipeline” via files**
- **IMOS/MACOS chosen due to unique capabilities that greatly facilitated the wavefront control simulation – IMOS & MACOS have a programming interface that avoids the “glueware” approach**
- **CODE V, OSLO, ZEMAX now (or will soon) possess similar capability**

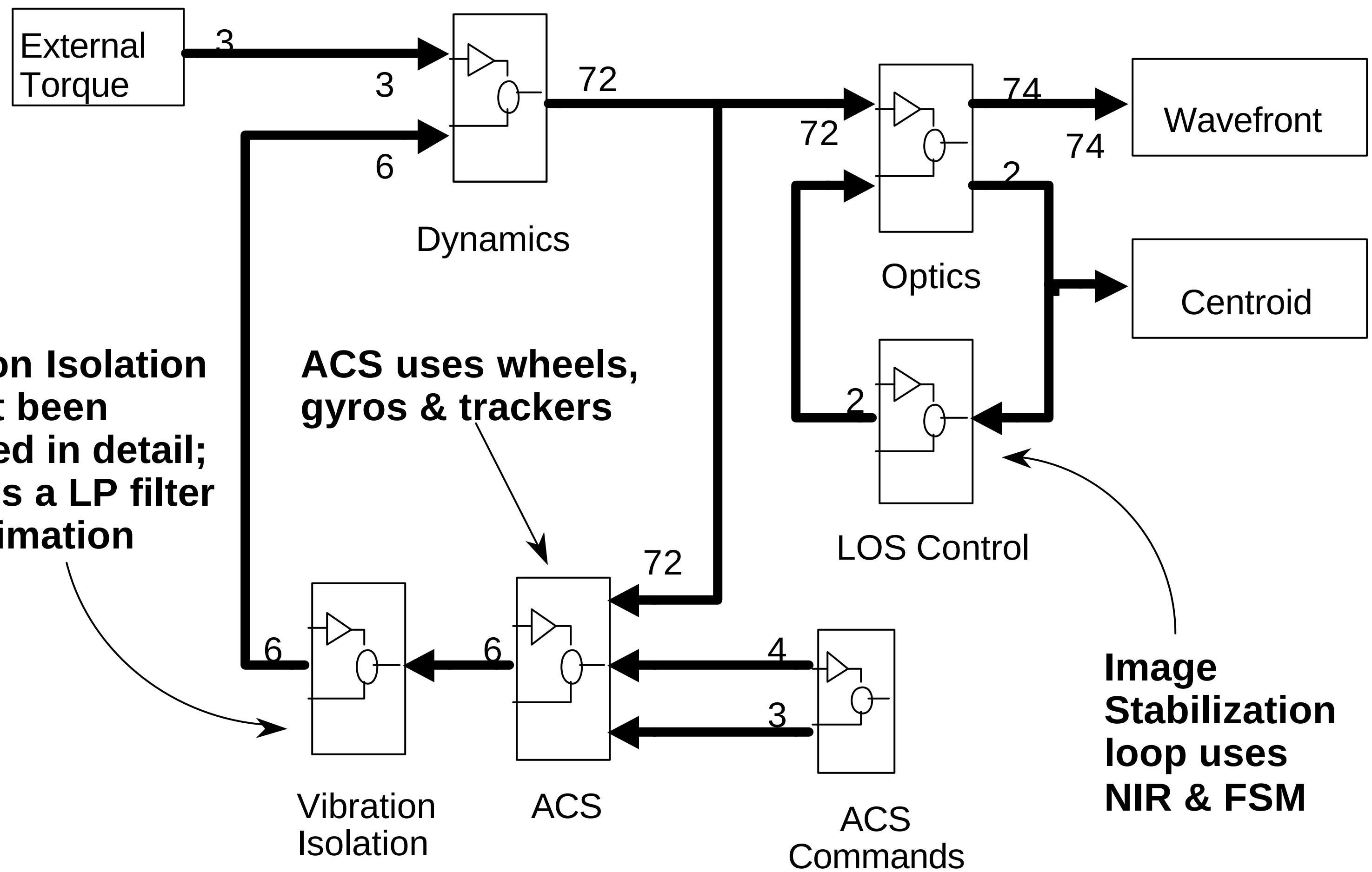
Design Verification Analysis Example #2

"Yardstick" Line-of-sight Stability

Example #2 Problem Statement

- Construct a model that simulates the line-of-sight stability of the system
  - Key assumption: only consider errors due to pointing/attitude sensor noise sources and reaction wheel imbalance loads
  - Key assumption: dynamic system is linear and time-invariant
  - Key assumption: modal damping factor is 0.1%
  - Given the top-level line-of-sight error allocation, perform a parametric analysis to determine the requirements for a reaction wheel vibration isolation system

Pointing Control System Block Diagram



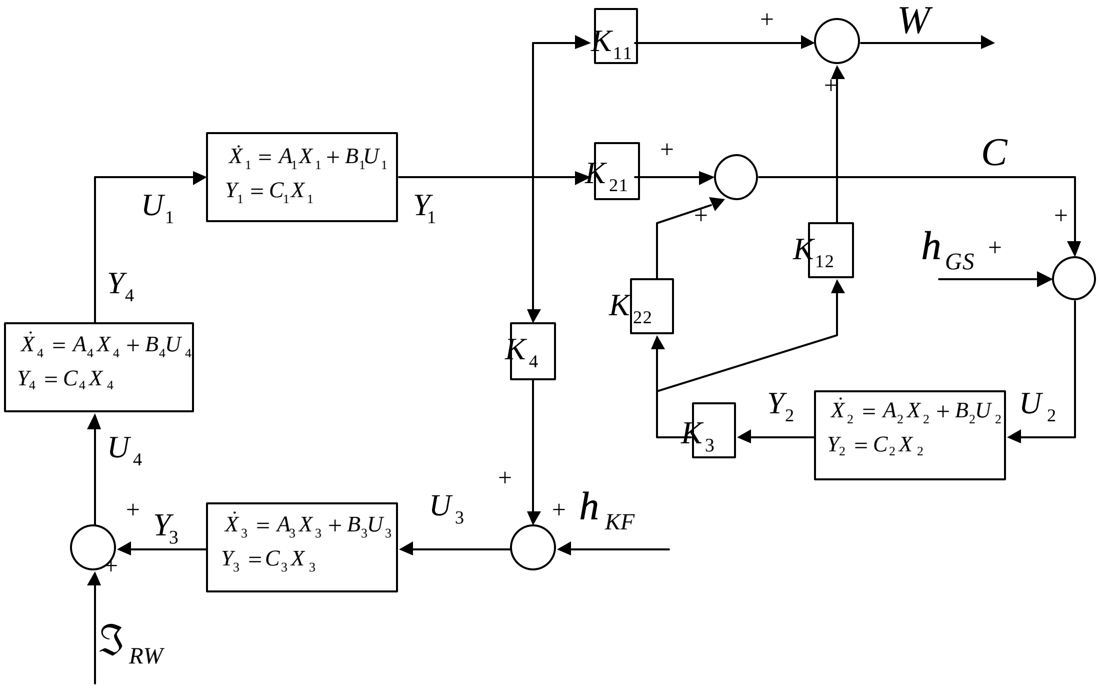
Vibration Isolation has not been designed in detail; model is a LP filter approximation

ACS uses wheels, gyros & trackers

Image Stabilization loop uses NIR & FSM

Simulation equivalent to XTE "Hi-Fi" built using visual modeling tool (Simulink™) in a fraction of the time

State-Space Model for Jitter Analysis



$$\dot{X} = AX + BU$$

$$Y = CX$$

$$\sigma_W = \sqrt{\frac{W^T W}{N_{rays}}} \qquad \sigma_C = \sqrt{C^T C}$$

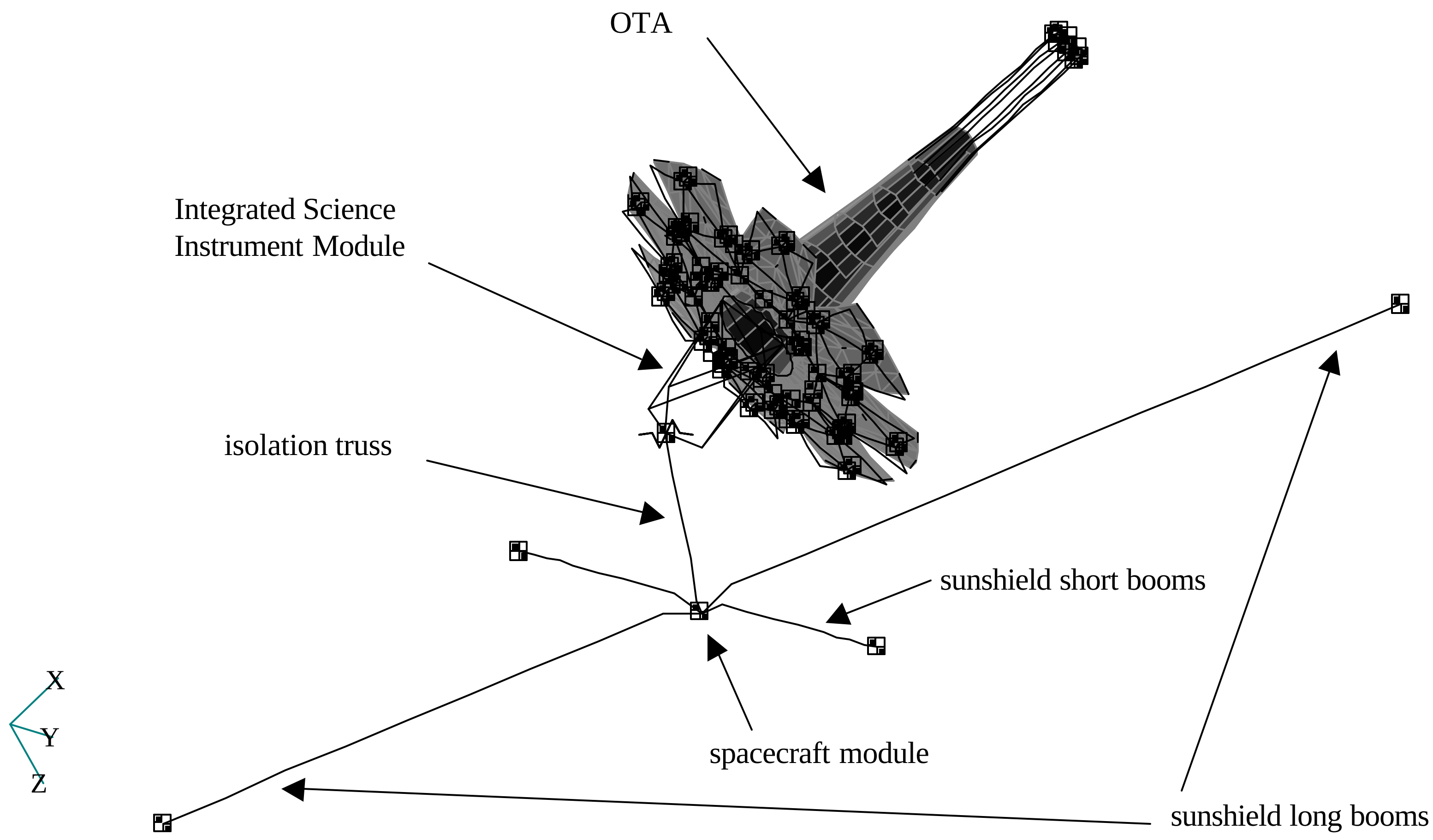
$$A = \begin{bmatrix} A_1 & 0 & 0 & B_1C_4 \\ B_2K_{21}C_1 & A_2 + B_2K_{22}C_2 & 0 & 0 \\ B_3K_4C_1 & 0 & A_3 & 0 \\ 0 & 0 & B_4C_3 & A4 \end{bmatrix} \quad X = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \quad U = \begin{bmatrix} h_{GS} \\ h_{KF} \\ \Im_{RW} \end{bmatrix} \quad Y = \begin{bmatrix} W \\ C \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ B_2 & 0 & 0 \\ 0 & B_3 & 0 \\ 0 & 0 & B_4 \end{bmatrix} \qquad C = \begin{bmatrix} K_{11}C_1 & K_{12}C_2 & 0 & 0 \\ K_{21}C_1 & K_{22}C_2 & 0 & 0 \end{bmatrix}$$

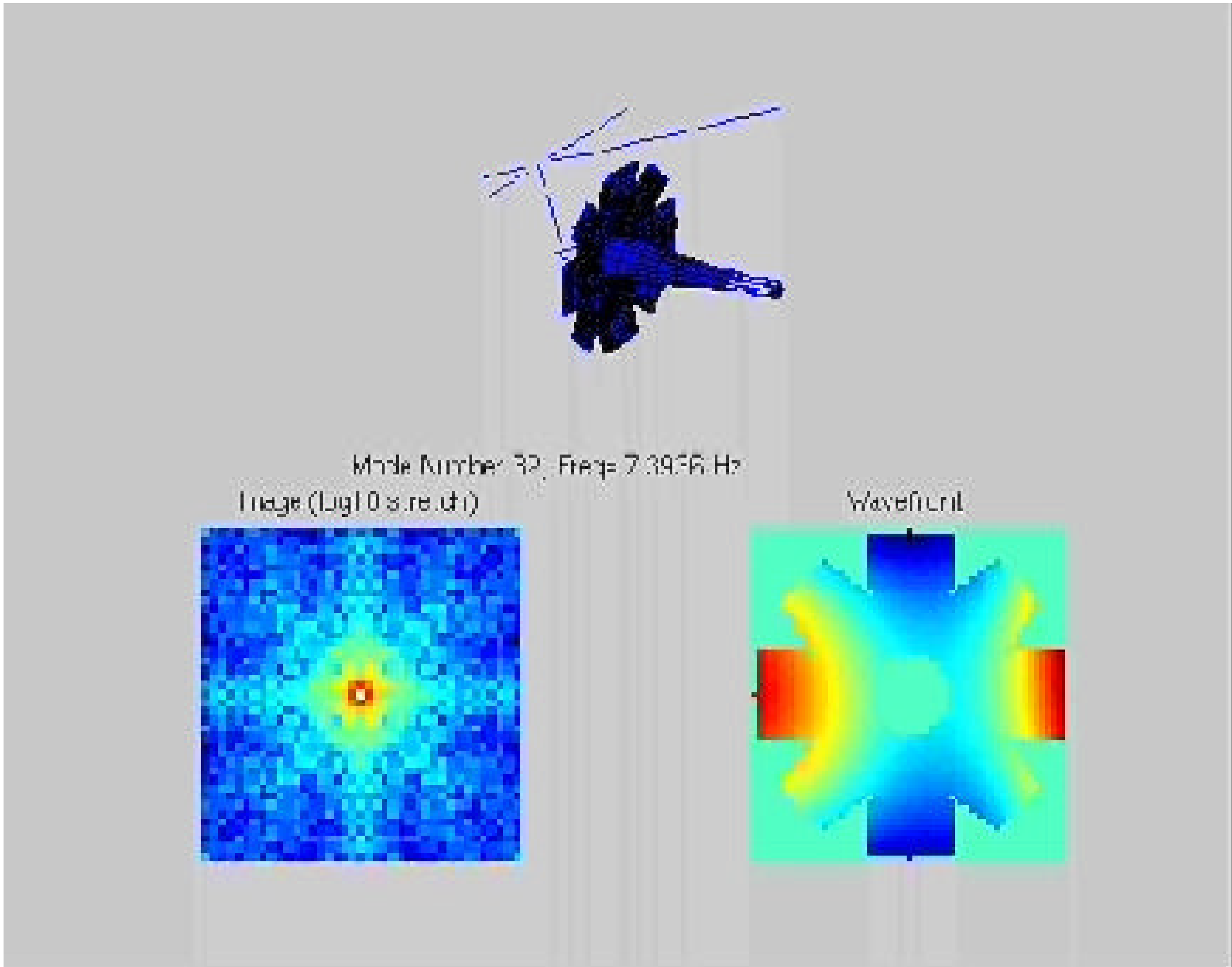
Developed in parallel with and traceable to the time-domain simulation – the latter was used to verify results from the linear analysis

Observatory FEM (IMOS)

Model contains ~5400 DOF, low- to –medium fidelity

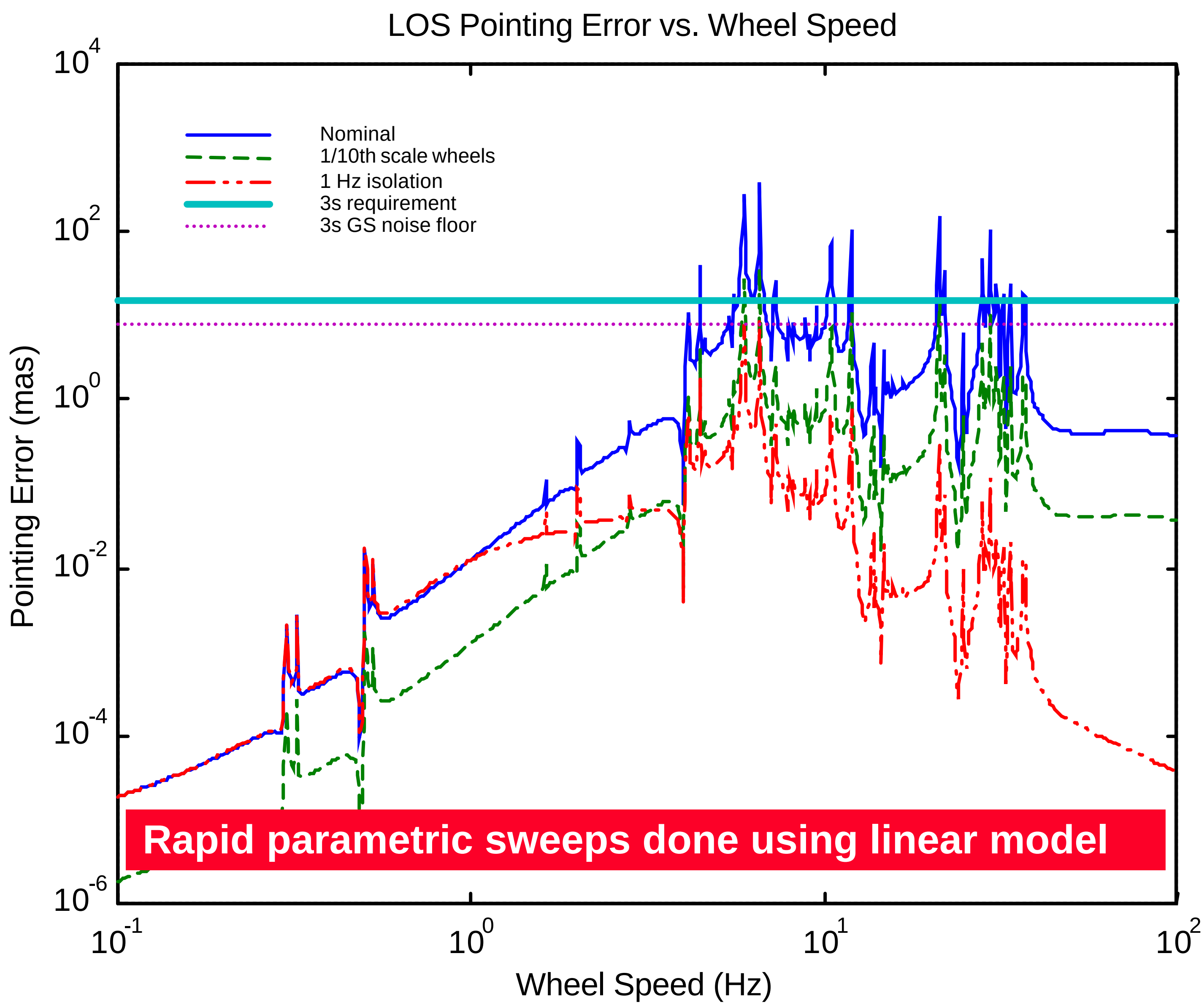


Opto-Mechanical Analysis



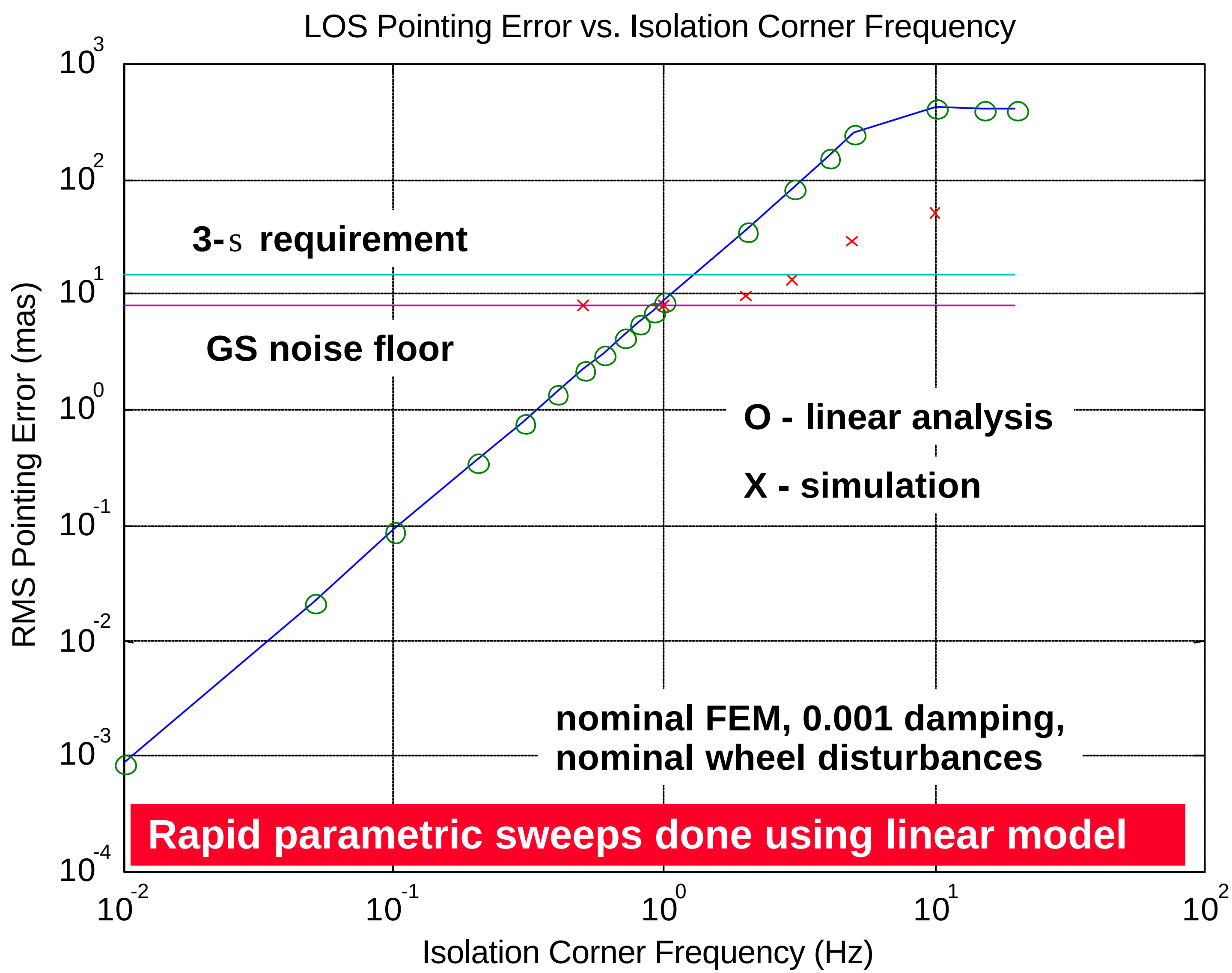
Structural dynamics (mode shapes) and equivalent aberrations are animated – visualization helpful to modeling team

Linear Analysis - Nominal Response, Effect of Isolation, Effect of Wheel Imbalance Magnitude



Rapid parametric sweeps done using linear model

How Much Isolation Is Required?



Sensitivity and "Iso-performance" Example

Nexus Flight Experiment

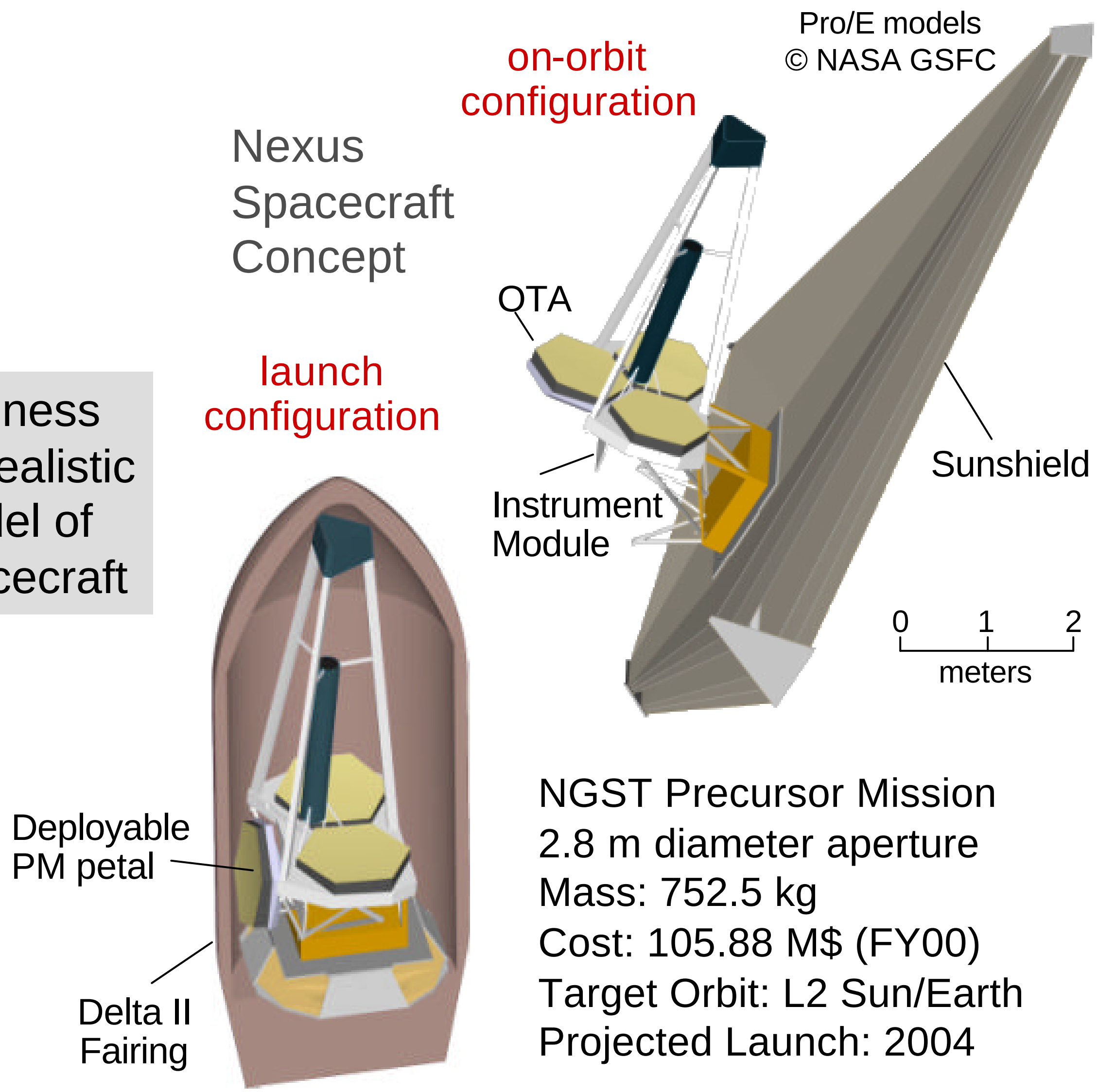
Example #3 Problem Statement

- **Essentially identical to previous example (line-of-sight stability problem)**
- **Exploit techniques recently developed at MIT in order to:**
  - **Compute key design sensitivities (changes in performance metrics as functions of changes in design parameters)**
  - **Enable intelligent design trades by identifying "iso-performance" contours in a multivariate design trade space**

Nexus Case Study @ MIT

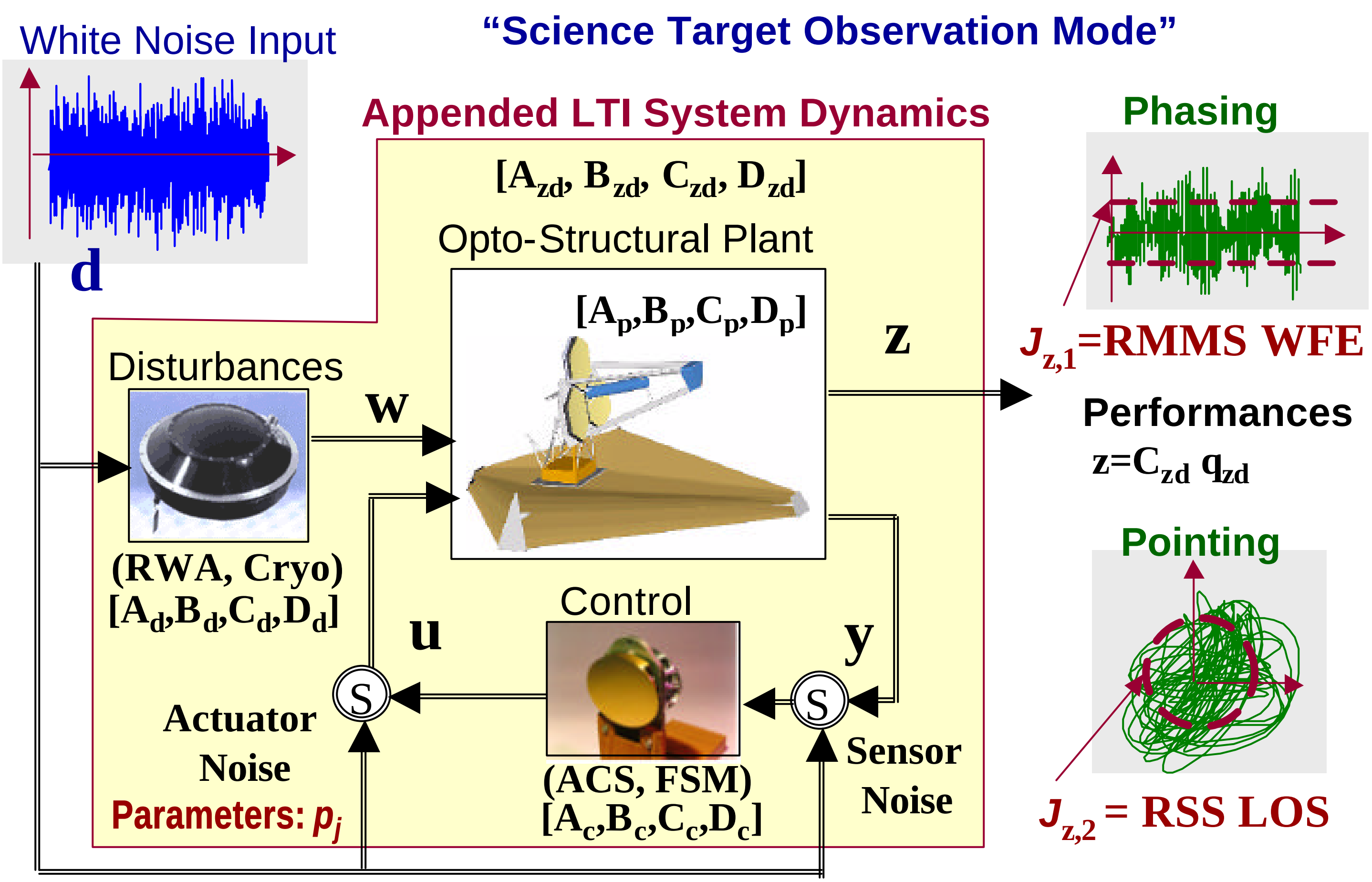
Demonstrate the usefulness of Isoperformance on a realistic conceptual design model of a high-performance spacecraft

Nexus Spacecraft Concept



NGST Precursor Mission
2.8 m diameter aperture
Mass: 752.5 kg
Cost: 105.88 M$ (FY00)
Target Orbit: L2 Sun/Earth
Projected Launch: 2004

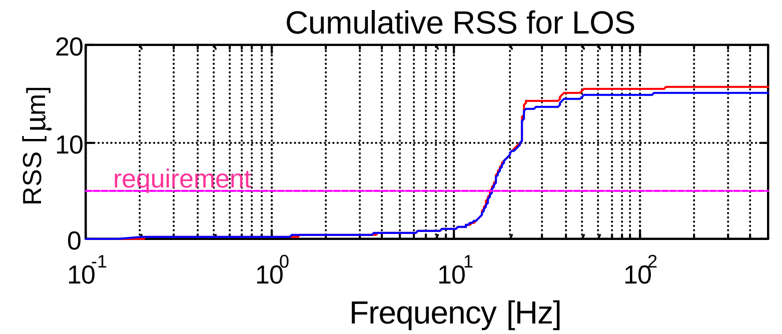
Problem Setting

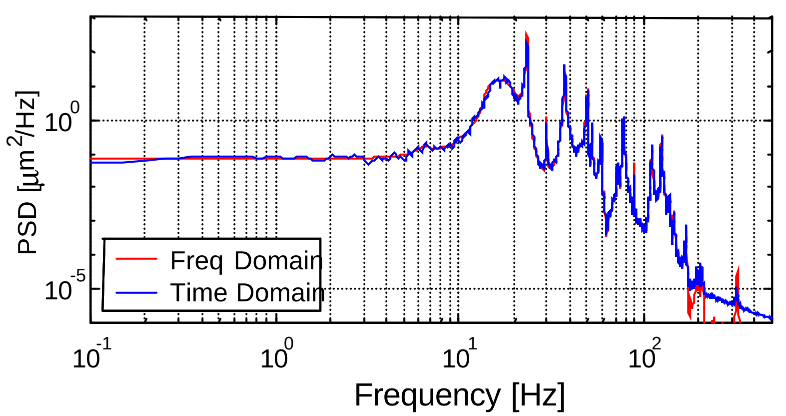


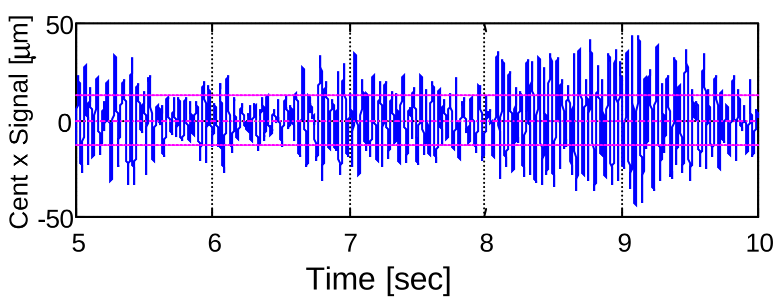
Traditionally: Define System Parameters $p_j = p_o$ ⟶ Predict H_2 performances $J_{z,i}$

Isoperformance: Find Locus of Solutions $p_{LB} < p_j < p_{UB}$ ⟵ Constrain performances $J_{z,i} = J_{z,req}$

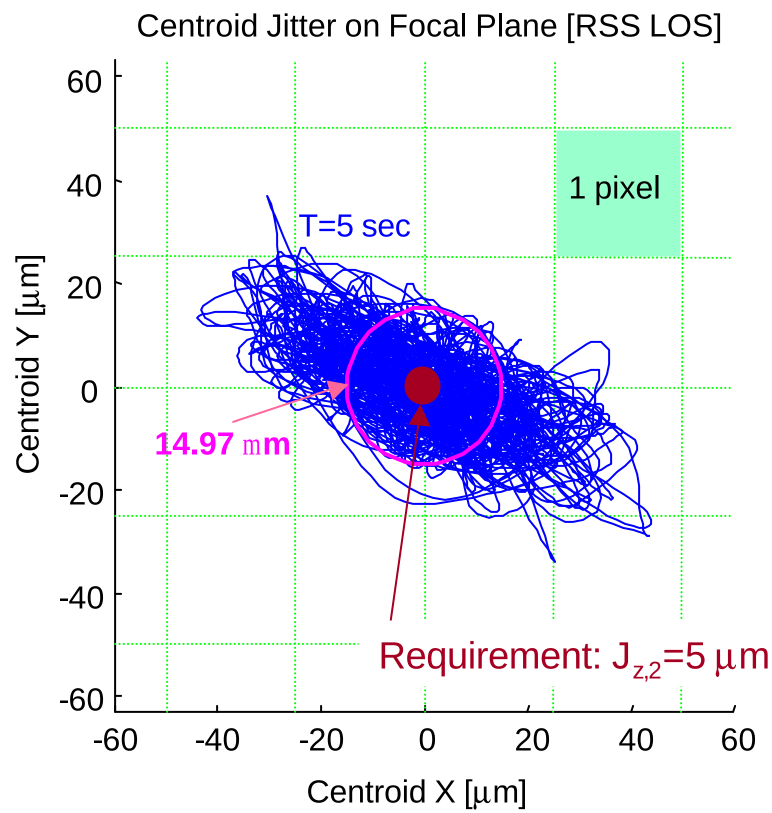
Initial Performance Assessment $J_z(p^o)$



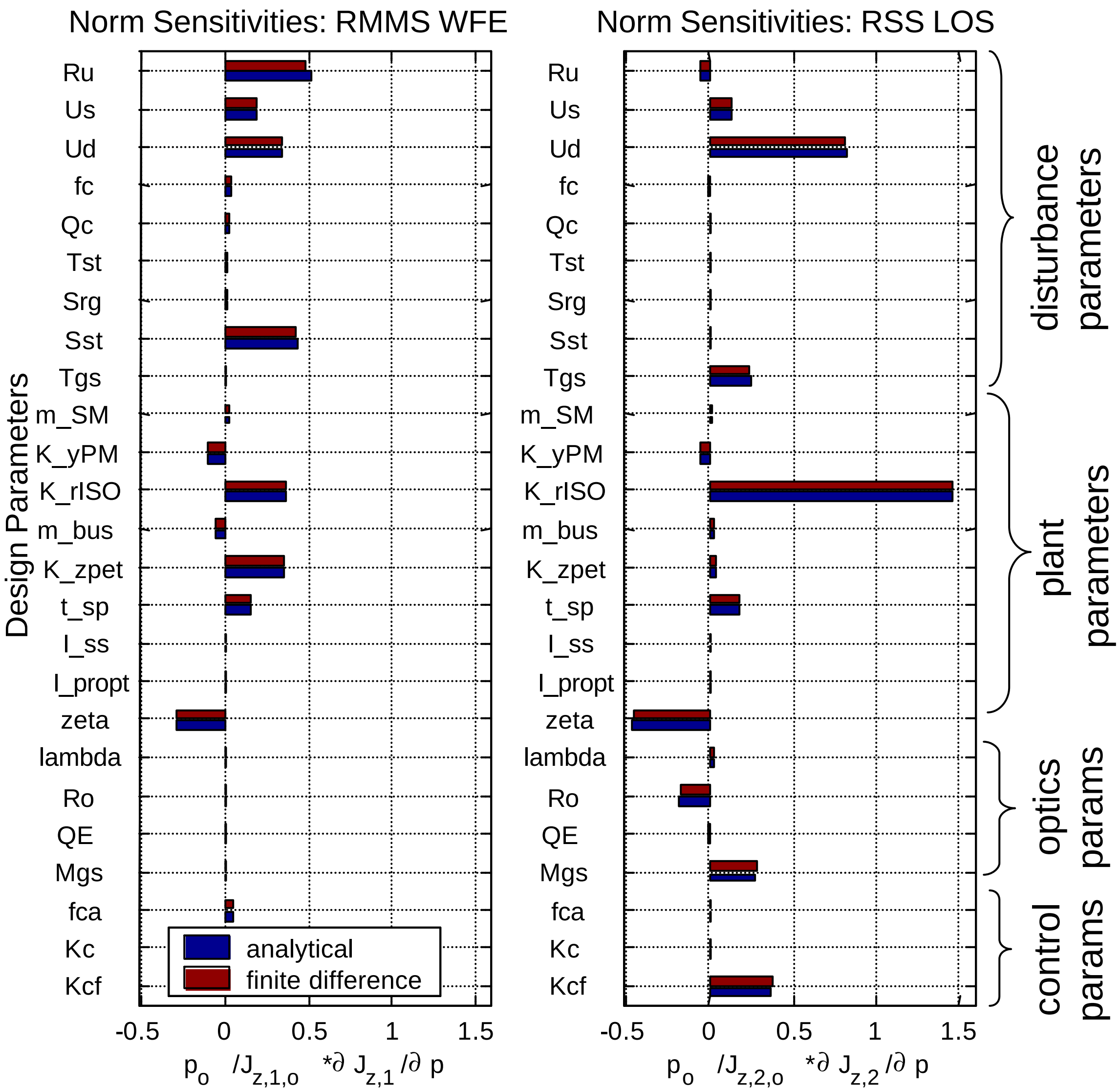




Results	Lyap/Freq	Time	
$J_{z,1}$ (RMMS WFE)	**25.61**	**19.51**	[nm]
$J_{z,2}$ (RSS LOS)	**15.51**	**14.97**	[µm]



Nexus Sensitivity Analysis



Graphical Representation of Jacobian evaluated at design p_o, normalized for comparison.

$$\bar{\nabla} J_z = \frac{p_o}{J_{z,o}} \begin{bmatrix} \frac{\partial J_{z,1}}{\partial R_u} & \frac{\partial J_{z,2}}{\partial R_u} \\ \cdots & \cdots \\ \frac{\partial J_{z,1}}{\partial K_{cf}} & \frac{\partial J_{z,2}}{\partial K_{cf}} \end{bmatrix}$$

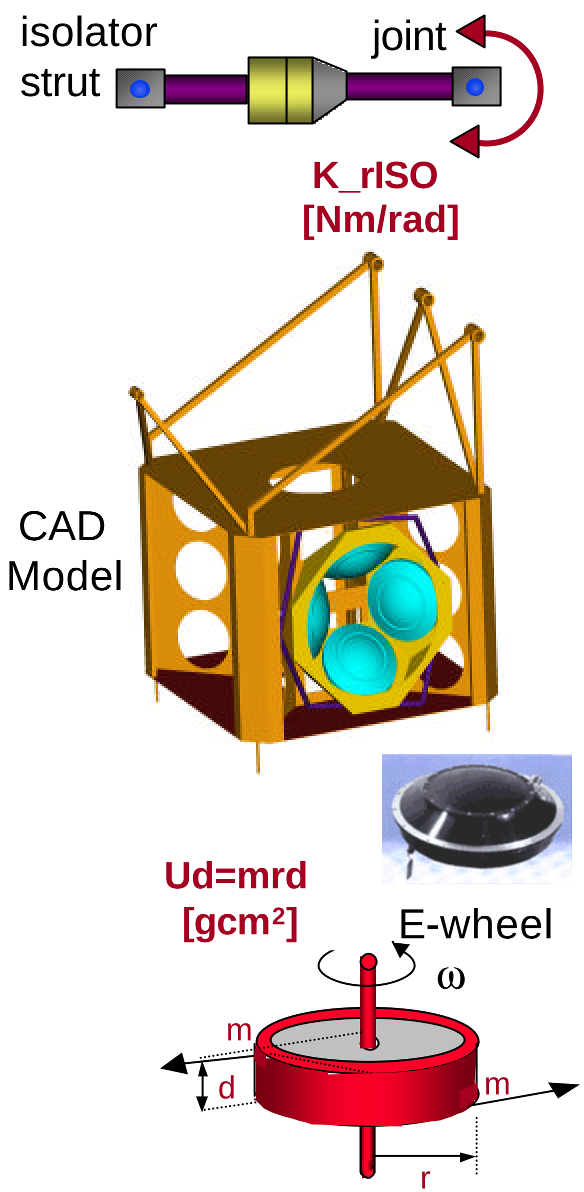
RMMS WFE most sensitive to:

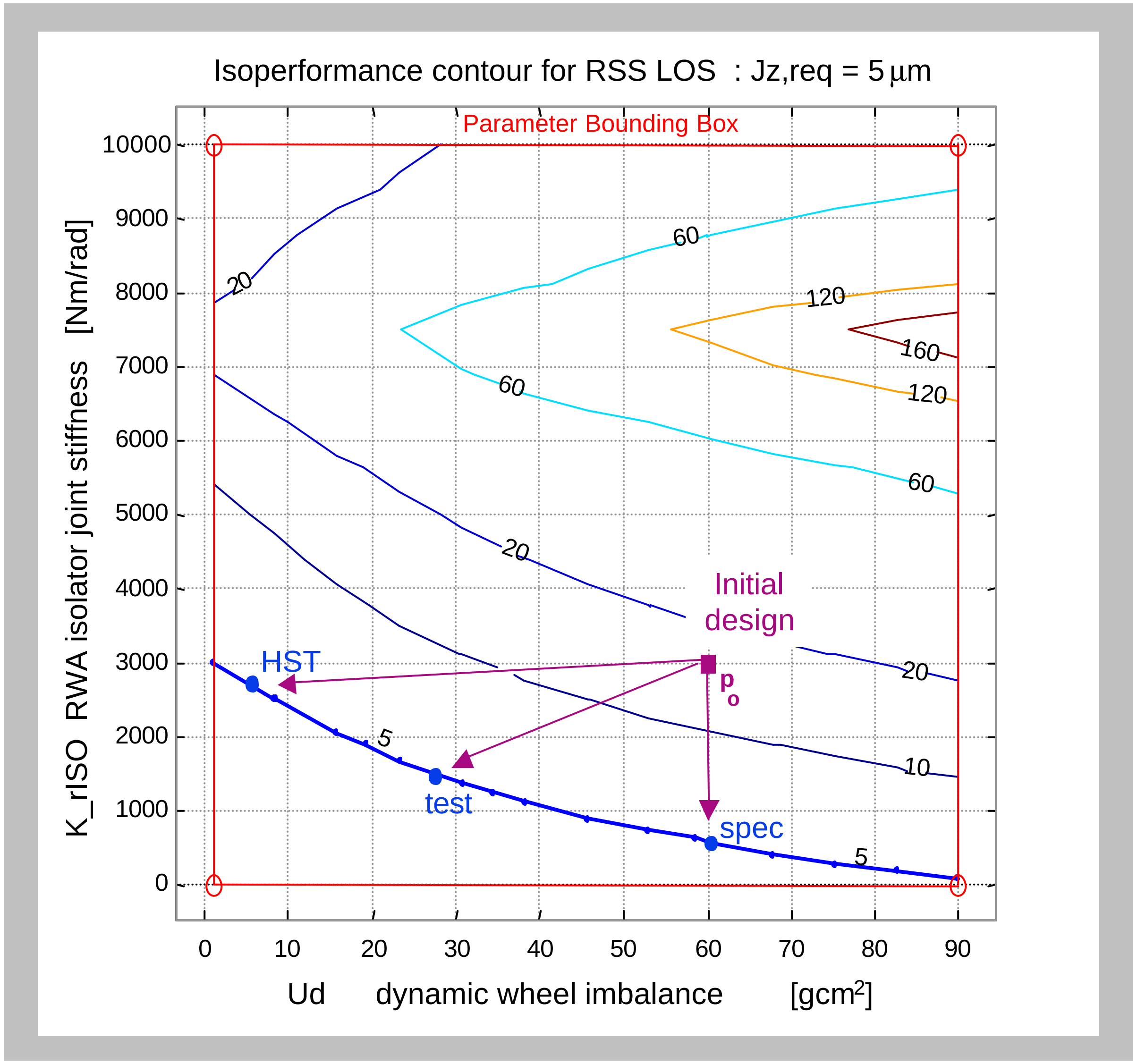
Ru - upper op wheel speed [RPM]
Sst - star track noise 1σ [asec]
K_rISO - isolator joint stiffness [Nm/rad]
K_zpet - deploy petal stiffness [N/m]

RSS LOS most sensitive to:

Ud - dynamic wheel imbalance [gcm^2]
K_rISO - isolator joint stiffness [Nm/rad]
zeta - proportional damping ratio [-]
Mgs - guide star magnitude [mag]
Kcf - FSM controller gain [-]

2D-Isoperformance Analysis





Multiobjective Design Optimization

Since solutions $\mathbf{p}_{iso}$ in the isoperformance set $\mathbf{I}$ do not distinguish themselves via their performance, we may satisfy **additional objectives**:

Performance $J_z(p_{iso}) = J_{z,req}$ √

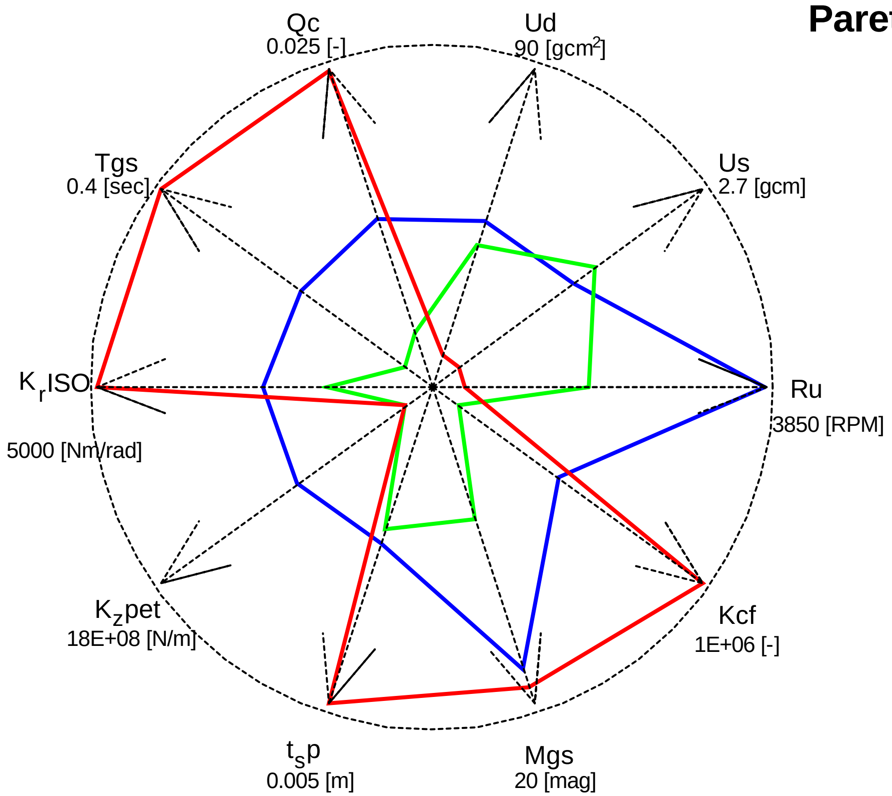
Cost Objectives J_c

- **Control effort**
- **Implementation Cost (mid-bound)**
- **System Mass**
- **Dissipated Power**
- **Closeness to "cheap" bound**

Risk Objectives J_r

- **Stability Margins (SISO)**
- **max SV of sensitivity function / mvar Nyquist**
- **Sensitivity of performance to parameter variations**
- **Knowledge Error**

Nexus Multivariable Isoperformance $n_p=10$



Pareto-Optimal Designs p^*_{iso}

Design A

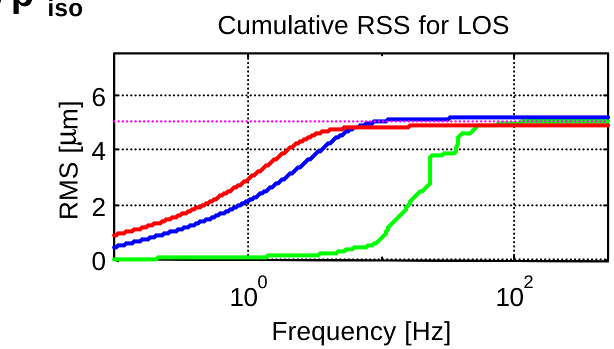
Best “mid-range” compromise

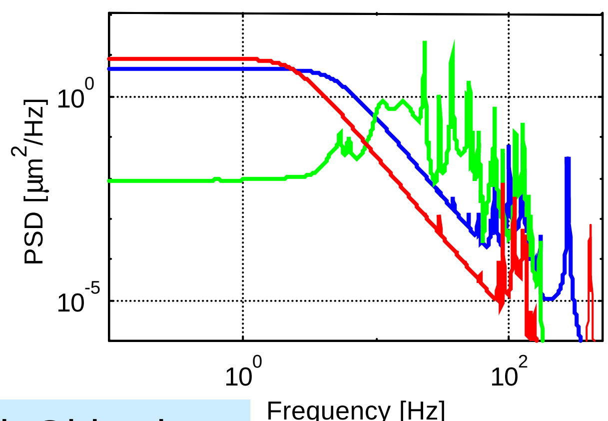
Design B

Smallest FSM control gain

Design C

Smallest performance uncertainty

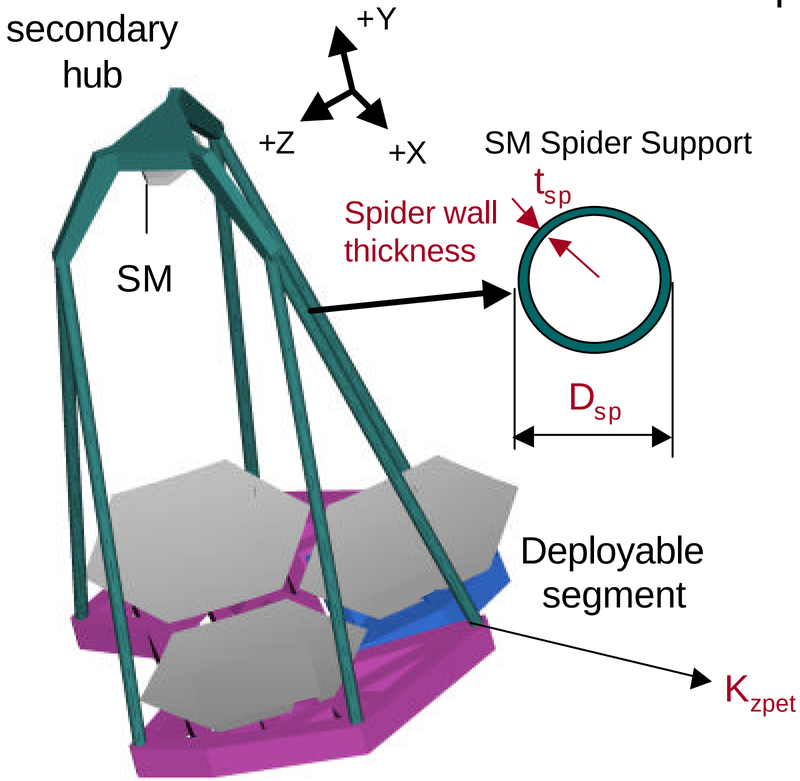




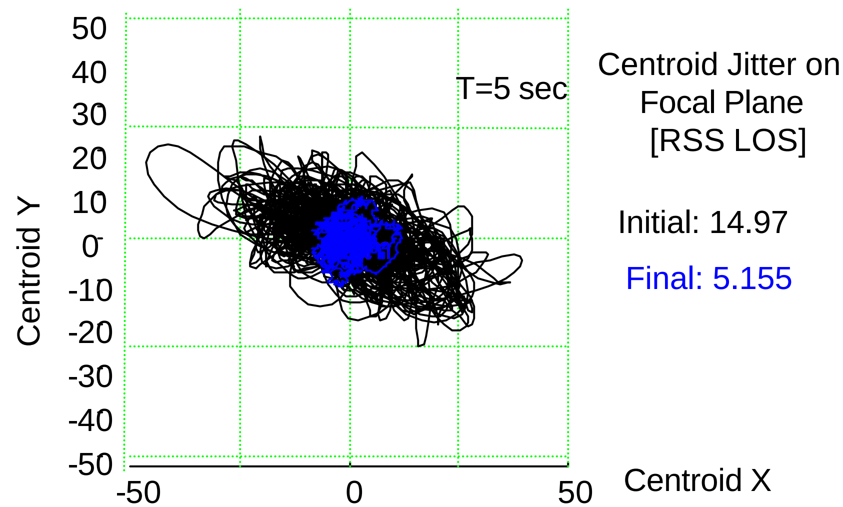
- A: min(J_{c1})
- B: min(J_{c2})
- C: min(J_{r1})

	Performance		Cost and Risk Objectives		
	Jz,1	Jz,2	Jc,1	Jc,2	Jr,1
Design A	20.0000	5.2013	0.6324	0.4668	+/- 14.3218 %
Design B	20.0012	5.0253	0.8960	0.0017	+/- 8.7883 %
Design C	20.0001	4.8559	1.5627	1.0000	+/- 5.3067 %

Nexus Initial p^{o} vs. Final Design p^{**}_{iso}

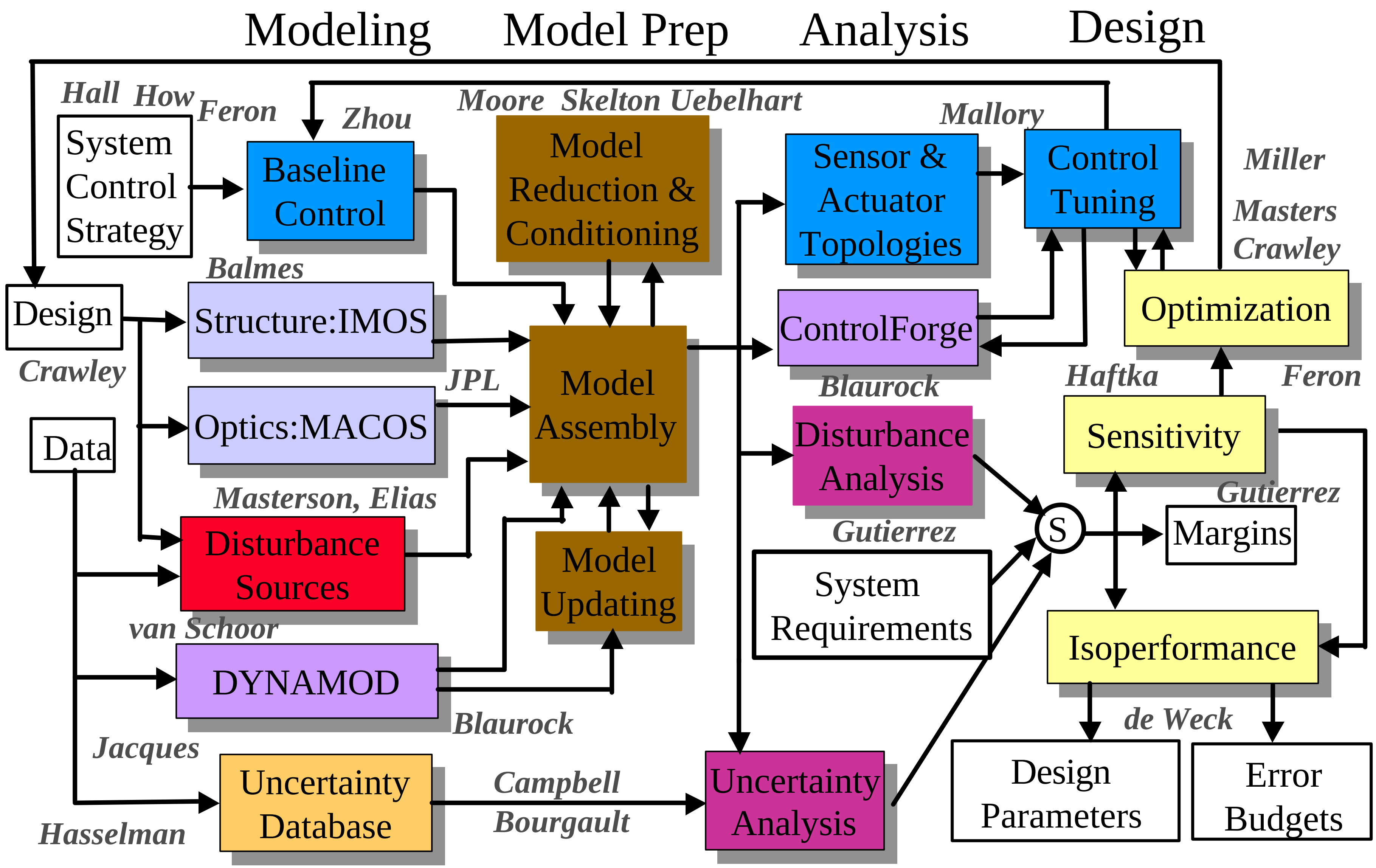


Parameters	Initial	Final	
Ru	3000	3845	[RPM]
Us	1.8	1.45	[gcm]
Ud	60	47.2	[gcm^2]
Qc	0.005	0.014	[-]
Tgs	0.040	0.196	[sec]
KrISO	3000	2546	[Nm/rad]
Kzpet	0.9E+8	8.9E+8	[N/m]
tsp	0.003	0.003	[m]
Mgs	15	18.6	[Mag]
Kcf	2E+3	4.7E+5	[-]



Improvements are achieved by a well balanced mix of changes in the disturbance parameters, structural redesign and increase in control gain of the FSM fine pointing loop.

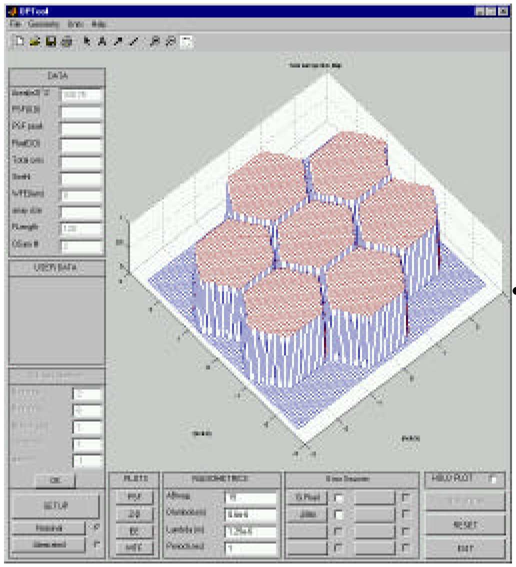
MIT – DOCS Framework

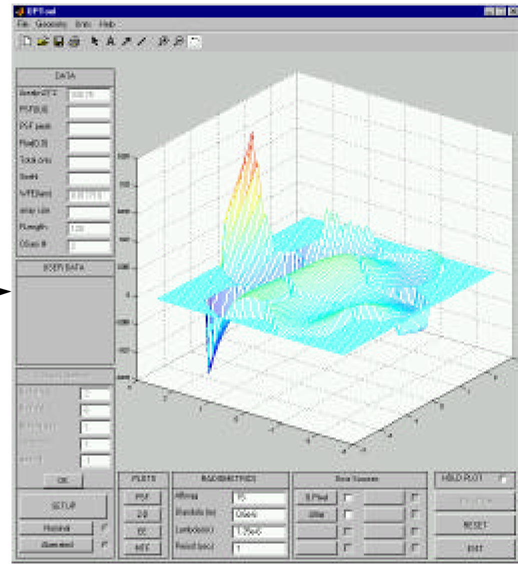


Requirements Analysis Examples

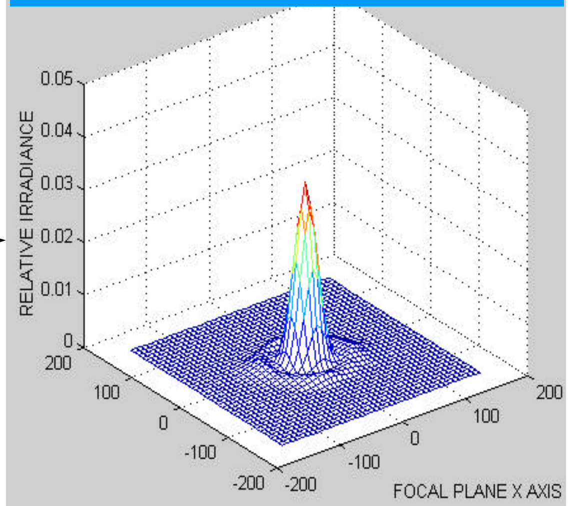
- Sensitivity (SNR) Analysis
- Wavefront Error Budget Partitioning

Sensitivity Analysis via Fourier Optics Modeling

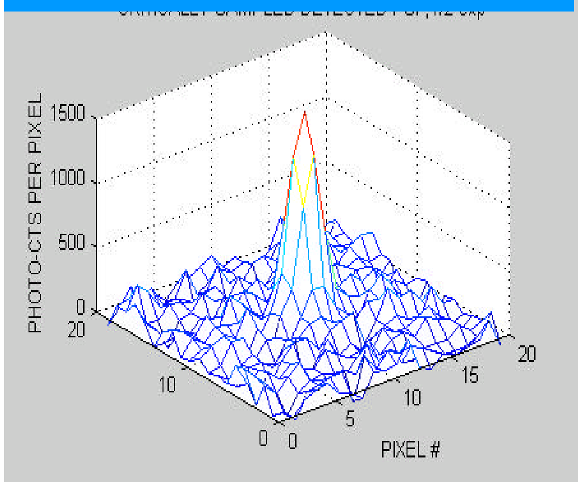




NOMINAL OPERATING WFE



DETECTED PSF



APERTURE GEOMETRY
PUPIL PHASE ERROR
JITTER
STAR MAGNITUDE
OPTICS THROUGHPUT
DETECTOR QUANTUM EFFICIENCY
DETECTOR DARK CURRENT
STRAY LIGHT & THERMAL EMISSION
ZODIACAL BACKGROUND
READ-OUT NOISE
FLAT FIELD ERRORS
A/D CONVERSION

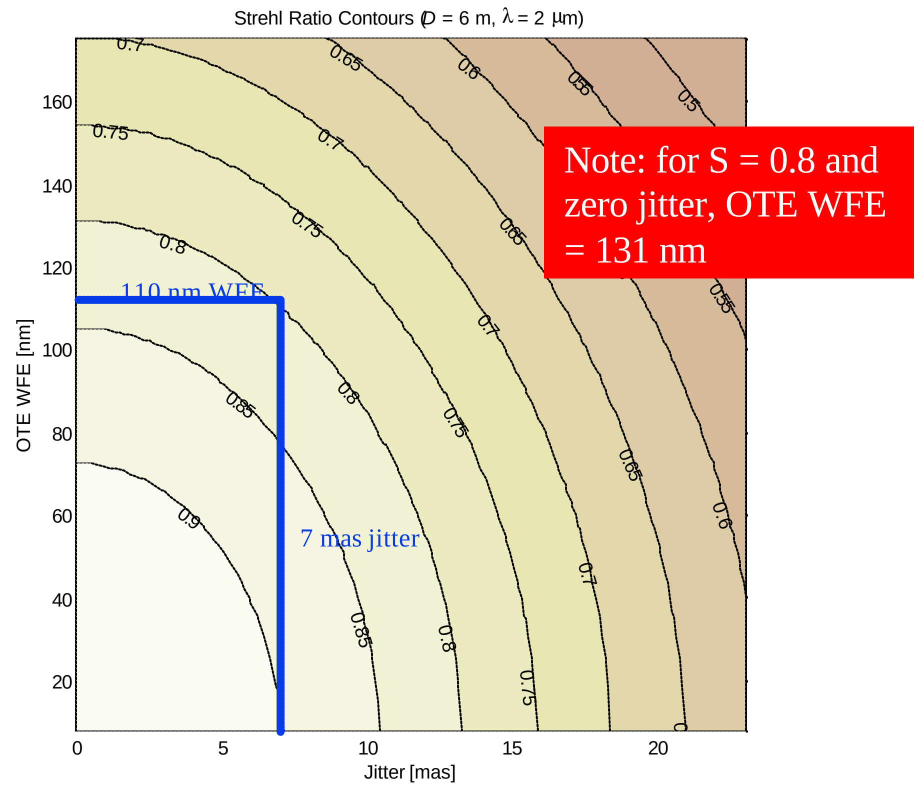
Wavefront Error Allocation Analysis

A simple derivation of the equivalency of jitter and RMS wavefront error…

$$S = e^{-\left(\frac{2\pi \sigma_{w}}{\lambda}\right)^{2}}$$

$$= \frac{1}{1+\left(2.22\, \sigma_{J} D/\lambda\right)^{2}}$$

$$\sigma_{w'} = \frac{\lambda}{2\pi}\sqrt{\ln\left[1+\left(2.22\, \sigma_{J} D/\lambda\right)^{2}\right]}$$



… leading to a model that provides contours of constant Strehl ratio as functions of jitter and "static" wavefront error

Examples Summary

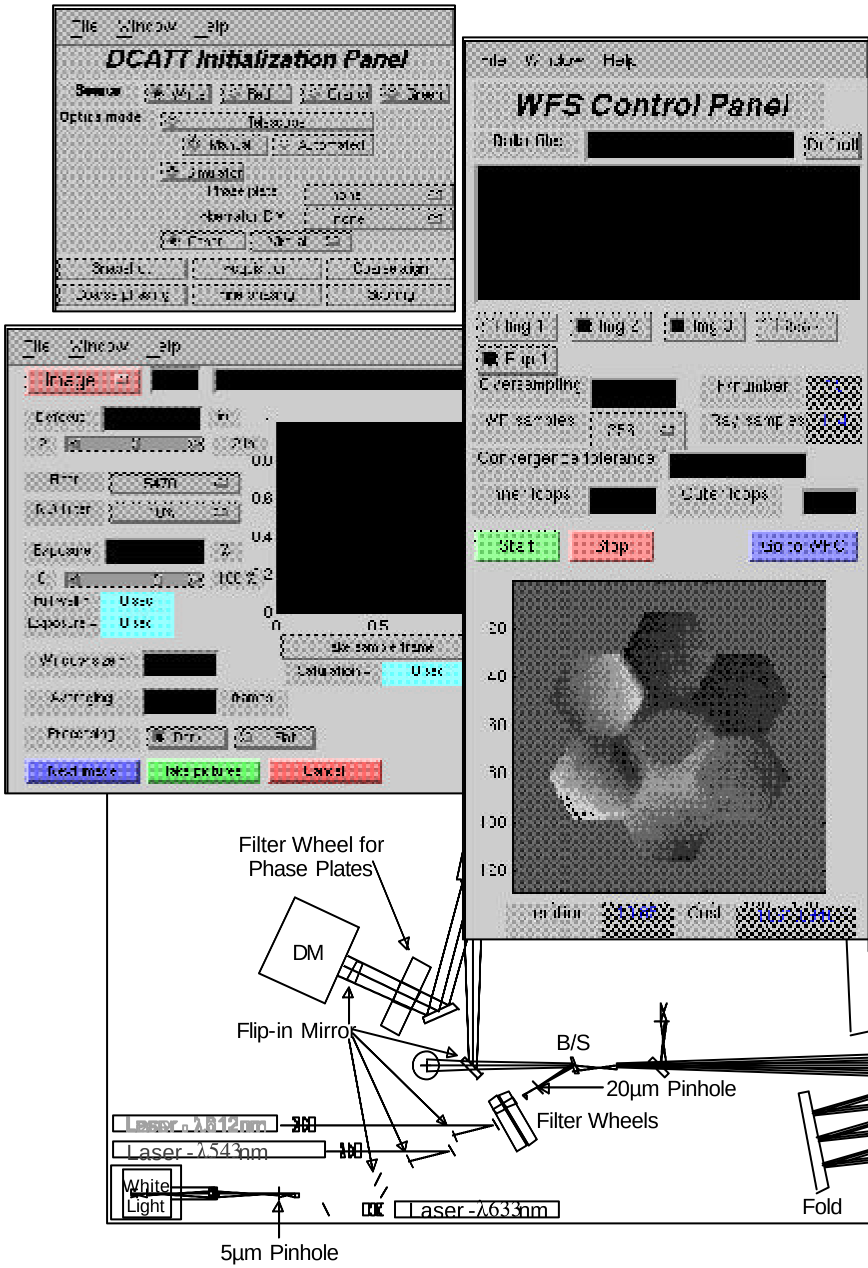
- From #1 → #5, complexity decreased: measured by model size (N_{DOF}), CPU/Memory load, and software development effort.
- From #1 → #3, number of free variables in model increased, and accordingly, so did the amount of "pre-work" (formulation of problem, solving of equations by hand before code was written, etc.).
- Examples #2 & #3 illustrate the use of "complementary" models – in these cases time-domain simulations used to cross-check results obtained using linear state-space models. The models in examples #4 & #5 are also complimentary.
- Examples #4 & #5, while being the simplest of these examples, are in a real sense the most powerful of all of these analyses, reason being that without good requirements, the rest of the "game" is pointless.
- WE (the "community", not just NGST) are typically better equipped in terms of tools, skills, and experience at solving problems such as #1 and #2 than any of the others.

Other Lessons Learned in NGST Phase I

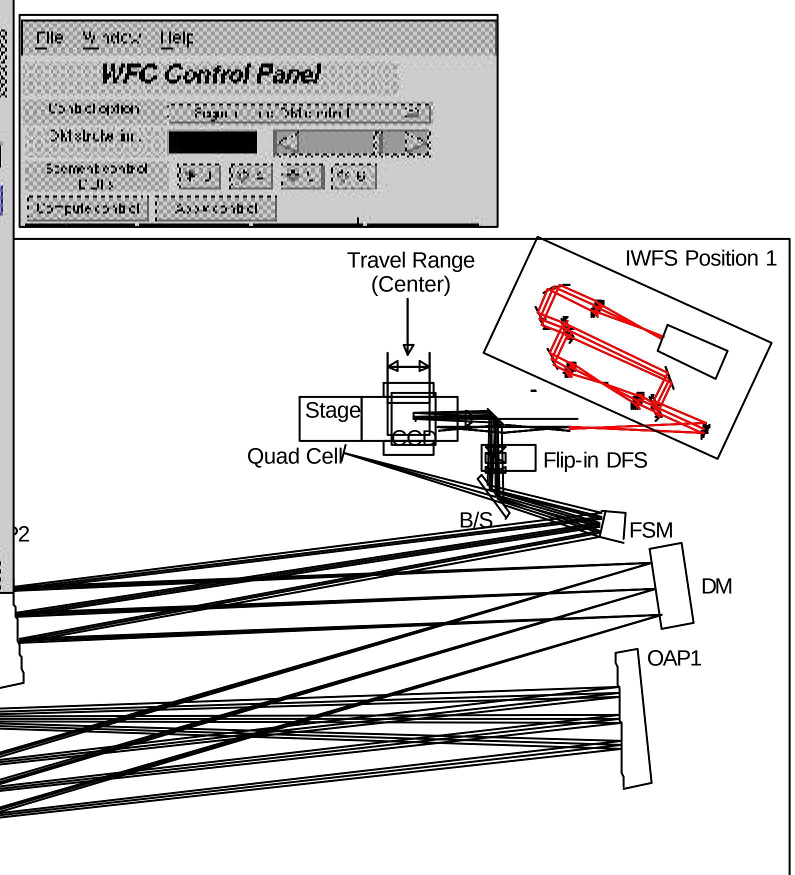
A Broader Perspective for Integrated Modeling

- **Return to the notion of a broader meaning for the word <u>integrated</u>…**
- **Modeling should be thoroughly *integrated* into the complete systems engineering organization/process/mindset**
  - **For an effort <u>*above a certain size*</u>, this almost certainly requires a team leader operating at the system level, not a discipline lead doing double-duty**
  - **Lead analyst needs to plan, communicate, resolve issues, maintain ultimate insight, enforce discipline on process**
  - **Make it clear what modeling can do**
  - **Make it clear what modeling cannot do (limitations, uncertainties)**
  - **Identify <u>needs</u> for modeling to be a success (schedule, manpower, budget, validation and verification methods)**
  - **Involve <u>key</u> project personnel in a rigorous model <u>validation</u> process**
  - **Establish regular and frequent communication (peer reviews, telecons, etc.)**

Things we do well: Exploit Testbeds at <u>Every</u> Opportunity



- Modeling has been and continues to be integral to the development of the control software and experiment plan for the DCATT (WCT) testbed
- Prediction/Measurement/Update cycles build confidence in modeling



Things WE could do better

Establish a process for timely model validation…

"All models are wrong, some models are useful" (George Box)

"An approximate answer to the right question is worth a good deal more than the exact answer to an approximate problem" (John Tukey)

Question/defend the choice of methods & tools…

"When the only tool you have is a hammer, then every problem begins to look like a nail" (Abraham Maslow)

Break the habit of reporting <u>nominal</u> and (so-called) <u>worst-case</u> results; develop efficient methods of rigorous statistical analyses

"Statistics in the hands of an engineer are like a lamppost to a drunk – they're used more for support than illumination" (A. E. Housman)

"Numbers are like people – torture them enough and they'll tell you anything" (unattributed)

Exploit Information Technology Solutions

- Collaboration is increasingly essential
- Configuration control of models & documents is critical
- Avoid, if possible, funneling all analysis through an individual or small cadre of experts – web-accessible models
- A disproportionate amount of time can be spent creating Powerpoint presentations in order to collaborate – sometimes unavoidable, but still wasteful
- E-mail as a means of communicating can be inefficient
- Computer security a concern for HTTP, FTP
- Do a better job of making our computers work for us in order to ease the burdens of both the team and the leader
- Specifics – segue to Johnny Medina…